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Complex Adaptive Systems and the Development of Force Structures for the United States Air Force

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Lieutenant Colonel, USAF

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Eric M. Murphy
Lieutenant Colonel, USAF

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Foreword

Force-structure analysis is the method by which the United States adapts and prepares for war, a process based on a century of industrial and economic prowess that has become—for better and worse—its de facto strategy. Force structure takes time to develop and make operational. Once established, it is costly and arduous to change. It can dictate policy options and in so doing sets the conditions for the next war. Colonel Murphy has critically examined the process and finds it lacking in an age in which change is the norm and the gap between the quick and the dead is expanding. He begins with a concise primer on complexity theory, the cutting edge of scientific understanding of organizations and networks, and distills it into a short but brilliant primer for military officers that should be used as a standard introduction throughout PME. In it, Murphy emphasizes that the guiding principles of operating in a highly volatile and rapidly shifting strategic landscape must be dynamic change, innovation, responsiveness, flexibility, and adaptability. More than critique, which he does with the scalpel-sharp incisiveness of an intellectual surgeon, he shows how this flexible manner of thinking can and should apply to all levels of military assessment. He then develops a three-part program to transition to an adaptive analysis and acquisition process. He begins by proposing a fresh set of measures for force-structure efficacy based not in industrial-era metrics but in concepts of adaptive value. He next offers a workable model for assessing and employing these measures and finishes with several thoughts on how changing the extant mentality from static or linear achievement to continuous improvement could be implemented in the force-structure-analysis community.

It is rare that a study as deeply analytical and mathematically precise as Murphy's is so brilliantly accessible. Indeed, he writes with such clarity and wisdom that the reader is both cerebrally sated and intellectually uplifted upon completion. Given the difficulty of the subject and the reluctance to change when one has been successful for so long—the US military has certainly been that—offering a paradigm shift as far-reaching and conceptually diametric as this is bound to meet with skepticism. But the future belongs to those who stand on the shoulders of visionaries who have gone before and can see beyond their limits. Eric Murphy is one of those exceptional intellects who has glimpsed the farther horizon and has the capacity and drive to haul the rest of us up to his vista.

Colonel Murphy's *Complex Adaptive Systems and the Development of Force Structures for the United States Air Force* received the 2012 USAF Historical Foundation award for the best School of Advanced Air and Space Studies

thesis in the field of security studies. I commend it to the reader as a sterling exemplar of the intimate relationship that exists between painstaking research and strategic vision.

Everett Dolman
EVERETT CARL DOLMAN, PhD
Professor of Comparative Military Studies
School of Advanced Air and Space Studies

About the Author

Lt Col Eric M. Murphy entered the United States Air Force through Officer Training School in 1997 after earning a bachelor of arts degree in English literature and a master of arts degree in mathematics from Eastern New Mexico University. His first assignment was as a test manager and operations research analyst with the Air Force Operational Test and Evaluation Center, Kirtland AFB, New Mexico. While there, he designed and led test activities to evaluate a variety of systems ranging from equipment to support combat search and rescue to architectures for the detection of threats from biological weapons. He then spent two years as an assistant professor and course director at the United States Air Force Academy and was competitively selected for assignment to the Air Force Institute of Technology's Civilian Institution Program to earn a doctorate in mathematics. After earning his PhD from Texas Tech University, Colonel Murphy was assigned to Headquarters Air Force, Studies and Analyses, Assessments and Lessons Learned (AF/A9). As an analyst on the Air Staff, he provided senior Air Force decision makers insight into future operations, war plans, and program alternatives. From there he moved to the Warfighting Analysis Division of the Joint Staff (J-8) where he provided support for senior leaders in the areas of force-structure and force-posture analysis. Following his tour on the Joint Staff, Colonel Murphy attended the School of Advanced Air and Space Studies at Maxwell AFB, Alabama. He then moved to Air Force Space Command at Peterson AFB, Colorado, where he led the development of strategic plans for the Air Force's space and cyberspace portfolios. Colonel Murphy is currently assigned as the commander of Air Education and Training Command's Studies and Analysis Squadron. He has deployed as an operational assessment analyst in the combined air and space operations center at Al Udeid AB, Qatar, and as the chief of force posture for the International Security Assistance Force (ISAF) Joint Command in Kabul, Afghanistan.

Acknowledgments

I would first like to thank the faculty and students who helped to make this year a time of challenge and growth. Proverbs 27:17 tells us, "Iron sharpeneth iron; so a man sharpens the countenance of his friend." You have all been my friends in this experience, and my mind and countenance are sharper for having known you all. I hope I've given as much as I've received. I would like to offer particular thanks to my advisor, Dr. Everett Dolman. I'm profoundly grateful for his tolerance, encouragement, and patience. After a year spent suffering my daily forays into his office, he may start locking his door, but I'm proud of the work we've done together this year, and I'm looking forward to our continuing collaboration.

I must also thank my parents. They were the first to teach me that books are my friends—a friendship I'm rethinking after a year at the School of Advanced Air and Space Studies—and they made me the person I am today. No matter how long my father is gone, his voice will always be the one I hear in my head telling me to be better and telling me I've made him proud—even when I fall. What better motivation can there be? In the words of Horatius, the Captain of the Gate (from Thomas Babington Macaulay's *Horatius*),

And how can man die better
Than facing fearful odds,
For the ashes of his fathers
And the temples of his Gods,

And for the tender mother
Who dandled him to rest.

Most importantly, I need to thank my wife. Her love and support through this year—and through all of our years—have kept me centered and sane. I can't even begin to tell her how important she is to me and how grateful I am to have her in my life. Someday I'll be worthy of all she gives me.

Abstract

Force-structure analysis—the mathematical and scientific discipline of assessing the utility of various material force structures—is critical to the process of planning, programming, and acquiring the military means to provide for national security and to shape the strategic environment. For this analysis to provide appropriate recommendations regarding force structure, however, it is vital that the prevailing analytic paradigm be consistent with the true nature of force structure, the environment, and their relationship to one another. This analysis presents a theory of complex adaptive systems and demonstrates that force structures are examples of such systems. The argument is then made that the prevailing paradigm of the force-structure-analysis community in the United States Air Force is inconsistent with this reality. A collection of recommendations identifies low-cost opportunities with the potential for significant long-term effects in aligning the force-structure-analysis paradigm with the fact that force structures are complex adaptive systems.

Chapter 1

Introduction

Among the many tasks the US military services are charged with is the responsibility to "determine Military Service force requirements and make recommendations concerning force requirements to support national security objectives and strategy and meet the operational requirements of the Combatant Commands."[1] In fulfilling this obligation, each of the services—as well as the Joint Staff and Office of the Secretary of Defense—employs a collection of scientists performing force-structure analysis to inform the process of planning, programming, and acquiring a material force structure. Thus, force-structure analysts are closely tied to the process of instantiating an ongoing development and implementation of service strategy—especially its material components—in the service of national security ends. To plan and execute effective strategy, however, "the strategist must comprehend the nature of the strategic environment and construct strategy that is consistent with it, neither denying its nature nor capitulating to other actors or to chance."[2] The great Prussian theorist of war, Carl von Clausewitz, echoes this philosophy: "First, the supreme, the most far-reaching act of judgment that the statesman and commander have to make is to establish . . . the kind of war on which they are embarking; neither mistaking it for, nor trying to turn it into, something that is alien to its nature."[3] The nature of the strategic environment deeply influences and in parallel is shaped by the type of war on which one embarks; these aspects of security and war are inextricably linked and codetermined. Force-structure analysts are neither commanders nor statesmen in the sense Clausewitz intended, of course, but they are nevertheless engaged in a strategic act. Their analyses inform the planning, programming, and acquiring of material force structures. These force structures are both elements and shapers of the environment. They are not only the tools of warfare but also the arbiters of what is potential in warfare. Or, in the words of Everett Dolman,

> In this broadest and most encompassing view, strategy represents the link between policy and military action. It connects the conduct of war with the intent of politics. It is subtler than the tactical and operational arts of directly matching means to ends, however. It shapes and guides military means in anticipation of an array of possible coming events. In the process, strategy changes the context within which those events will happen. Thus strategy, in its simplest form, is a plan for attaining continuing advantage. For the goal of strategy is not to culminate events, to establish finality in the discourse between states,

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This paper was the author's 2012 thesis for the School of Advanced Air and Space Studies; some data reflects this time frame.

> but to influence states' discourse in such a way that it will go forward on favorable terms. For continue it will.[4]

Force-structure analysts—not only statesmen, commanders, and strategists—must consider the role of strategy as a component of the critical process of realizing military means. It is important that they, too, grasp the nature of the strategic environment and the kind of war—analytic war—on which they are embarked. This paper is devoted toward this purpose.

This discussion advances the proposition that force structures and the strategic environments they create are complex adaptive systems. That is, force structures are comprised of diverse, interdependent, adaptive elements interacting nonlinearly and exhibiting systemic behaviors including emergence, coevolution, and path dependence across multiple scales. This conception of force structure and the strategic environment leads directly to a discussion of desirable elements for material force structure and the requirements of force-structure analysis. Harry Yarger, professor of national security studies at the US Army War College, eloquently characterizes these aspects:

> Thus, the world is more a place of instability, discontinuity, synergies, and unpredictability than planners prefer. Although a meaningful degree of linearity can be achieved, results often vary from the original intent, at times costing more than anticipated because of the need to manage the chaos within the strategic environment over the strategy's timeline. Thus, in the strategy process, a scientific analysis must be combined with historical perspective to create a comprehensive strategy that provides for dynamic change, innovation, responsiveness, flexibility, and adaptability. The art of strategy allows the strategist to see the nature of the strategic environment and a path or multiple paths to his desired end-states; and the scientific aspect of strategy provides a disciplined methodology to describe the path in a rational expression of ends, ways, and means that shape the strategic environment in favorable terms.[5]

Unfortunately, the Air Force community of force-structure analysts explicitly and systematically fails in its treatment of material force structure and the strategic environment as a complex adaptive system. In doing so, the strategic ends Yarger articulates—dynamic change, innovation, responsiveness, flexibility, and adaptability—are not specified in the process of force-structure analysis. This persistent failure to correctly characterize the nature of the environment and the material force structures defining and defined by that environment admits a category of unrecognized risk for not only the force structure of the US Air Force but also the national security needs that force structure exists to serve.

The divide between the complex adaptive nature of force structure and its environment and the general linear reality implicit in US Air Force approaches to force-structure analysis is not unbridgeable.[6] With limited investment and disruption, the prevailing paradigm in the force-structure analysis community

can be realigned in the long term and made consonant with the true nature of force structure, the strategic environment, and the problem of planning, programming, and acquiring force structures. Importantly, this change of paradigm must continue to honor the requirement to eventually instantiate a force structure. The end product of force-structure analysis will inform a recommendation for the programming and acquisition of a particular force. The key distinction is that these recommendations will be shaped by an understanding of force structure as it is rather than as one might wish it to be.

This discussion proceeds in four phases with the objective of developing a theory of complex adaptive systems as it pertains to force structure and then applying that theory to recommend actions. First, in the words of the Chinese philosopher Confucius, "If names be not correct, language is not in accordance with the truth of things. If language be not in accordance with the truth of things, affairs cannot be carried on to success."[7] Recognizing this, chapter 2 develops a working definition of complex adaptive systems and elucidates their characteristics using a variety of scientific traditions.[8] In chapter 3, force structure is placed within the context of the theoretical construct developed in chapter 2. This chapter suggests that force structure—and the mutually determined environment created by interacting force structures—is precisely depicted as a complex adaptive system.[9] While the theory of complex adaptive systems has gained considerable notice and been applied in numerous ways in both military and nonmilitary milieux, chapter 4 argues that this has not occurred in the force-structure-analysis community of the Air Force. Finally, chapter 5 advances a set of proposals aligning the force-structure-analysis community in the Air Force with the model of force structures as complex adaptive systems—closing the gaps identified in chapter 4. Recommendations include the privileging of different measures of force-structure efficacy, using new models for describing these measures, and implementing education and training programs for the force-structure-analysis community.[10]

Notes

(All notes appear in shortened form. For full details, see the appropriate entry in the bibliography.)

1. Department of Defense Directive 5100.01, *Functions of the Department of Defense*, 27.
2. Yarger, *Strategy and the National Security Professional*, 28.
3. Clausewitz, *On War*, 88.
4. Dolman, *Pure Strategy*, 6.
5. Yarger, *Strategy and the National Security Professional*, 33. This statement recapitulates Beyerchen, "Clausewitz, Nonlinearity, and the Importance of Imagery," 70–77.
6. The concept of a general linear reality is taken from the work of sociologist Andrew Abbott, who argues that "there is implicit in standard methods a 'general linear reality' (GLR), a set of deep assumptions about how and why social events occur, and that these assumptions

prevent the analysis of many problems interesting to empiricists and theorists alike." These assumptions include that the social world consists of fixed entities with variable attributes, cause cannot flow from the small to the large, causal attributes have only one casual pattern, outcomes are sequence independent, careers of entities are independent, and causes are independent. See Abbott, "Transcending General Linear Reality," 169.

7. Confucius, *Analects*, 13.3.

8. Essentially, this portion of the discussion comprises the first two aspects of Winton's characterization of the functions of theory: definition and Cartesian reductionism in the form of categorization. See Winton, "On the Nature of Military Theory," 20–21. The irony in applying reductionist thinking in the construction of a definition for complex adaptive systems—a discipline that rejects reductionism—is not lost on the author.

9. This depiction of force structure represents Winton's third and fourth functions of theory. The characterization of force structure as a complex adaptive system explains its behavior. Further, this connects the study of force structure to the study of other complex physical, biological, and social systems (ibid., 21).

10. The recommendations represent Winton's last function of theory since anticipation or prediction provides prescription for action (ibid.).

Chapter 2

Complex Adaptive Systems: A Primer

In his 1637 treatise *A Discourse on Method*, French philosopher and mathematician René Descartes characterized his view of the scientific method by a strict adherence to four principles. First, he committed himself to take no scientific assertion on faith.[1] Second, he dedicated himself to ensuring his investigations omitted no possibilities. To these he added the personal resolutions "to divide all the difficulties under examination into as many parts as possible, and as many as [are] required to solve them in the best way" and to begin his investigations "with the simplest and most easily understood objects, and gradually ascending, as it were step by step, to the knowledge of the most complex."[2] Descartes's statement offers perhaps the clearest and most succinct possible articulation of scientific reductionism. Shaped by an overarching metaphor of the universe and all its components as a clockwork mechanism, this reductionism avers that any complex whole can be understood by disaggregating it into its components and analyzing their individual behaviors.[3] Indeed, the word *analysis* is defined as the separation of a whole into its constituent parts and is derived from the Greek *αναλυει*, meaning "to break up."[4] Implicit in this reductive vision of the universe as a clockwork mechanism governed by Newtonian mechanics—where the whole is equal to no more and no less than the sum of its parts—is a belief in the predictive power of the analytic process. The French mathematician Pierre-Simon Laplace describes this potential for prediction in his 1814 work *A Philosophical Essay on Probabilities*:

> Present events are connected with preceding ones by a tie based on the evident principle that a thing cannot occur without a cause which produces it. . . . We ought then to regard the present state of the universe as the effect of its anterior state and as the cause of the one which is to follow. Given for one instant an intelligence which could comprehend all the forces by which nature is animated and the respective situation of the beings who compose it—an intelligence sufficiently vast to submit these data to analysis—it would embrace in the same formula the movements of the greatest bodies of the universe and those of the lightest atom; for it, nothing would be uncertain and the future, as the past, would be present to its eyes.[5]

This vision of predictability in the behavior of the universe began to come under attack shortly after the publication of Laplace's *Essay*, however. Henri Poincaré, writing on the character of various forms of chance, was led by the following argument to the conclusion that prediction is at least problematic, if not impossible:

> If we could know exactly the laws of nature and the situation of the universe at the initial instant, we should be able to predict exactly the situation of this same universe at a subsequent instant. But even when the natural laws should have no further secret for us, we could know the initial situation only *approximately*. If that permits us to foresee the subsequent situation *with the same degree of approximation*, this is all we require, we say the phenomenon has been predicted, that it is ruled by laws. But this is not always the case; it may happen that slight differences in the initial conditions produce very great differences in the final phenomena; a slight error in the former would make an enormous error in the latter. Prediction becomes impossible and we have the fortuitous phenomenon (emphasis in original).[6]

He goes on to describe the weather as an example of a system in which such small errors of approximation may yield disproportionately divergent outcomes. While meteorologists may be aware that a cyclone is likely to arise and wreak havoc on some location in the near future, a difference or error in measurement as small as one-tenth of a degree may lead the cyclone to spread "its ravages over countries it would have spared."[7] With this insight, Poincaré characterized in the nineteenth century what meteorologist Edward Lorenz would later name the "butterfly effect." In this is seen the beginning of a field of inquiry usually referred to as chaos theory—the study of nonlinear dynamical systems like the weather.[8]

In recent years, more fundamental questions have been asked of the reductionist worldview espoused by Descartes. Specifically, it has been observed that in innumerable systems—including stock markets, ecosystems, and the organisms comprising those ecosystems—the behavior of the overall system is not implicit in the behavior of its individual elements. In these systems, behavior at the system level is a phenomenon emerging not only from the behavior of the individual components comprising the system but also from the interaction of those components and their adaptations to one another. In an explicit rejection of the clockwork universe of Descartes and Newton, one can say that in these systems, the whole is greater than the sum of its parts. Not only is prediction problematized by nonlinearity and uncertainty, the very analytic act of decomposition renders understanding of systemic phenomenon impossible. The study of these systems—usually referred to as complex adaptive systems—generally falls under the rubric of complexity theory.[9]

Developing a precise and universally agreeable definition of the intellectual field of complexity theory is challenging since, as the sociologist Sylvia Walby observes, "complexity theory is not a unified body of theory; it is an emerging approach or framework. It is a set of theoretical and conceptual tools; not a single theory to be adopted holistically."[10] Equally challenging is establishing a specific and universal definition of complexity and, by extension, complex adaptive systems—the type of system investigated here. Physicist Seth Lloyd,

for example, compiled a collection of over 40 measures of complexity organized into three categories (measures of difficulty of description, difficulty of creation, and degree of organization), with each definition implicitly describing a more or less unique concept for complexity.[11]

Similarly, one can attempt to define a complex adaptive system in terms of either its characteristics (i.e., What is it?), its behavior (i.e., What does it do?), or some mixture of these. That is, one can focus on the element level, the system level, or some middle ground. Complexity theorist Scott Page, for example, characterizes complex systems at the element level as consisting of "diverse entities that interact in a network or contact structure—a geographic space, a computer network, or a market. The entities' actions are interdependent—what one protein, ant, person, or nation does materially affects others. . . . Often scholars distinguish between complex systems—systems in which the entities follow fixed rules—and complex adaptive systems—systems in which the entities adapt."[12] On the other hand, Melanie Mitchell offers a pair of complementary definitions focused at the systemic and behavioral levels. In her definitions, a complex system involves either "large networks of components with no central control and simple rules of operation giv[ing] rise to complex collective behavior, sophisticated information processing, and adaptation via learning or evolution" or "nontrivial emergent and self-organizing behaviors."[13] In this analysis, a complex system is defined heuristically as a hybrid of these two approaches. That is, it will be taken to constitute diverse, interdependent, adaptive elements interacting nonlinearly and exhibiting systemic behaviors including emergence, coevolution, and path dependence across multiple scales. Each of these conceptual components forming a mental model for complex adaptive systems is described next.

Diversity

On first examination, the concept of diversity seems straightforward. Intuitively, a population or collection of elements is diverse if "composed of distinct or unlike elements or qualities."[14] To apply the concept of diversity to the study of complex systems, though, and to answer the question of "what kind of diversity, when, and under what conditions produces good outcomes . . . in systems with what kind of characteristics" requires a more robust and mathematically precise characterization.[15] Since no single measure captures every aspect of difference relevant to every problem, however, multiple characterizations of diversity provide insight into different aspects of a population. Page describes two classes of diversity of interest here: within types (or variation) and across types (entropy, distance, and attributes).[16]

Standard measures of variation within type—variance and the coefficient of variation—are familiar from introductory statistics. Given a finite set of observed values $\{x_i\}_{i=1}^{n}$ for some population characteristic, the arithmetic mean (average) value of the observations is given by the formula

$$\mu = \frac{1}{n}\sum_{i=1}^{n} x_i,$$

and the variance is given by

$$\sigma^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \mu)^2.$$

This measure of variation has units associated with it, and, as such, it must always be interpreted in light of those units. Thus, comparisons of diversity (or variation) across populations with different means—especially when those means are of a different order—and dissimilar units can be problematic. One solution is to normalize the variation, reducing it to a dimensionless quantity called the "coefficient of variation":

$$c_\upsilon = \frac{\sigma}{\mu}.$$

Neither of these quantities is perfect or universally applicable, of course. Each has strengths and weaknesses—and both require that the observations involve quantitative measures—but carefully used together they allow for a greater understanding of diversity within types.[17]

Diversity across type is more complex in its measurement and generally less familiar, but, as previously noted, there are three basic approaches to its measurement. The first measure for diversity across type entails characterizing observed entropy (broadly speaking, an indication of the number of types within a population and the evenness with which the population is distributed over those types). Given a collection of observations $\{p_i\}_{i=1}^{n}$, where p_i denotes the proportion of the total population comprised of the *i*th type and requiring

$\alpha \geq 0$ and $\alpha \neq 1$, a general expression for entropy—sometimes called Rényi entropy[18]—is given by the formula

$$G_n^a = \left(\sum_{i=1}^{n} p_i^a \right)^{\frac{1}{1-a}} .$$

This very general measure is seen in a variety of fields. For example, when $\alpha = 2$, economists will recognize a form of the Herfindahl-Hirschman Index while ecologists will recognize a close cousin of Simpson's index.[19] Just as the measures of variability described above each had strengths and weaknesses, so does entropy. The most obvious weakness is that type difference is essentially binary; two objects are either of the same type, or they are not.[20] Thus, entropy measures fail to account for the fact that while a German Shepherd, Labrador Retriever, and Siberian tiger are all of different types, the two dog species resemble each other more than either resembles the tiger.[21]

A comparative metric characterizing the absolute dissimilarity of types (rather than the distribution of a population across types, as entropy does) is the distance between the two types. To calculate a distance between two points in space is a simple matter, but to define a more general idea of distance that can capture the difference between a dog and a cat is more complex.[22] Writing in the *Quarterly Journal of Economics*, Martin Weitzman proposes a quite general concept of distance derived from the idea of ancestral taxonomy and an associated characterization of the diversity of a population based on that distance. As an example of how this distance works, consider a strictly notional evolutionary or taxonomic tree depicting the relationship among species (see fig. 1). The distance between two species is simply the vertical distance across taxonomic levels to a common ancestor for those two species. Thus, the German Shepherd and Labrador Retriever are closer together (separated by a distance of one) than either is to the tiger (distance of three from both). Further, all are closer to each other than any is to the turtle (distance of four for each).[23] Such a concept of distance may be applied to any collection of objects that can be related according to such a diagram.[24] From this distance function, the Weitzman diversity of the system given by the taxonomic tree can be described by the sum of the lengths of the branches on the evolutionary tree.[25]

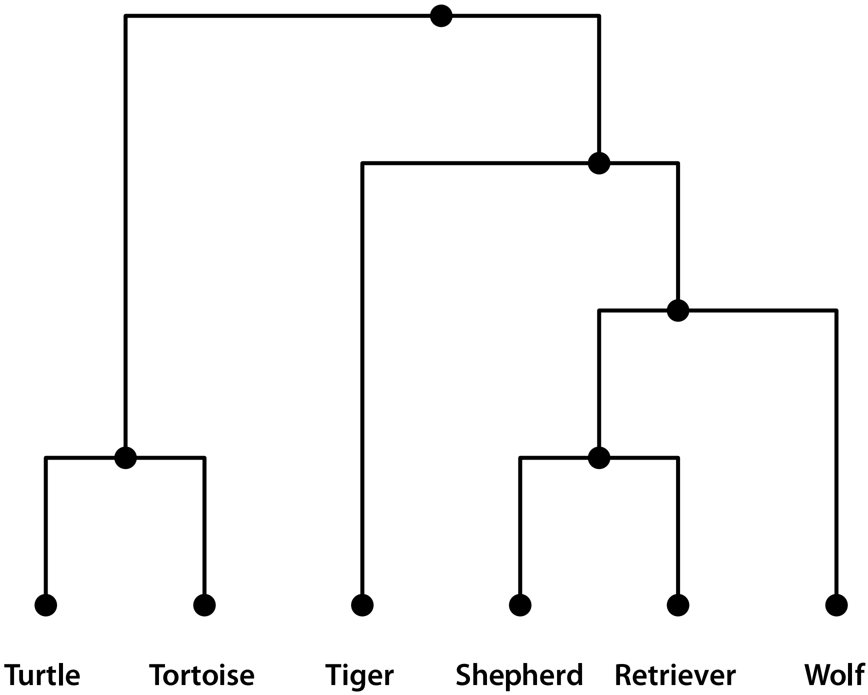


Figure 1. Evolutionary tree and taxonomic distance. (*Adapted from* Martin L. Weitzman, "On Diversity," *Quarterly Journal of Economics* 107, no. 2 [May 1992]: 363–405, by permission of Oxford University Press.)

An interesting combination of entropy and distance to derive a measure is sometimes called the effective number of species. Two species that are effectively identical are considered nearly the same species and—when counting total species—together add only slightly more than one to the total.[26] To obtain such a metric, begin with a distance function $d(\cdot,\cdot)$ describing the dissimilarity between types (e.g., the taxonomic distance described above). For every species type i and j in the population, define a similarity matrix Z by the relation $Z_{ij} = e^{-d(i,j)}$. The number of effective species is then given by the formula

$$\|Z\| = \sum_{i,j} (Z^{-1})_{ij}.$$

Consider, for example, two objects p_1 and p_2 that differ by the quantity $d(p_1,p_2)$ varying from zero (the two objects are identical) to infinity (the two objects are perfectly unique with respect to each other). The number of effective species/objects described by the metric $\|Z\|$ as a function of this abstract distance function is illustrated in figure 2. Notice that the number of effective objects varies from one to two as the observed distance between the two objects varies from zero (identical) to infinity (unique).[27]

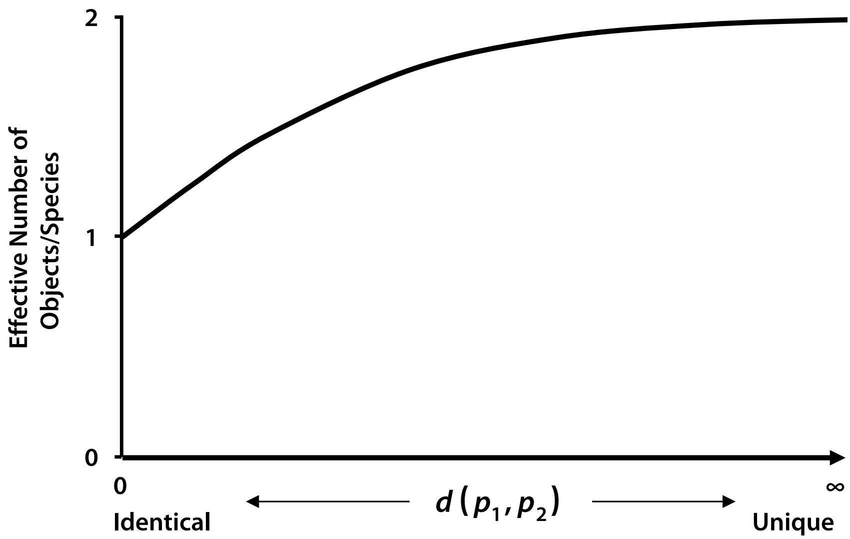


Figure 2. Number of effective objects/species. (Unless otherwise noted, figures were developed by the author.)

Page offers a third approach to describing the diversity of a system across types that counts the unique attributes represented in the system: attribute diversity. In considering the attributes present in the system and describing the attribute diversity of the system, however, there are supplemental concerns regarding transferability and separability that may be important. These deal with the ability of the system under examination to evolve by transferring attributes to one another (transferability) and to function effectively in some task with only a subset of the given attributes (separability). Attributes that are separable and transferable imply an agile population in the sense that the characteristics of the population may be combined freely to generate new types in the system as circumstances demand.[28]

Interdependence

The elements of a complex adaptive system are said to be interdependent in that the fitness of the elements is mutually defined. An especially intuitive illustration is the so-called predator-prey model describing the dynamic, interdependent relationship between predators (e.g., foxes) and their prey (e.g., rabbits). Put simply, the basic predator-prey equations assume that (1) in the absence of the other species, the prey population will increase exponentially without bound while the predator population will decrease exponentially and that (2) the rate with which predator and prey interact is proportional to the product of their population sizes.[29] Under these assumptions, the predator population is described by growth based on the supply of prey species (food) taken together with a natural death rate. Similarly, change in the population of prey is based on its own growth rate taken together with the rate at which it is preyed upon.[30] An example of the population dynamics for such a model is shown in figure 3. The interdependence between the species in this model is clear. As the predators reduce the prey population, they deplete their own food source and begin to die off. As the predator population decreases, however, the prey species are able to reproduce quickly enough to replenish their numbers; the predators respond to this increased bounty by increasing their own numbers. This drives down the prey population, and the cycle (nearly) repeats.

Examples of systems with interdependencies like these are innumerable, of course. Brian Arthur illustrates the problem of interdependence in the so-called bar problem: each potential patron of a bar decides whether or not to go to the bar based on his or her expectation regarding the number of others who will also go (too many patrons render the bar unpleasantly crowded, and the patron will stay home). If each potential patron operates on an uncoordinated, inductive prediction of the next week's likely attendance at the bar, the performance of each patron is a function of the behaviors of the other patrons. The patrons are interdependent.[31] Eric Beinhocker whimsically describes these interdependent expectations: "What you do depends on what you expect me to do, which in turn depends on what I expect you to do, and so on."[32]

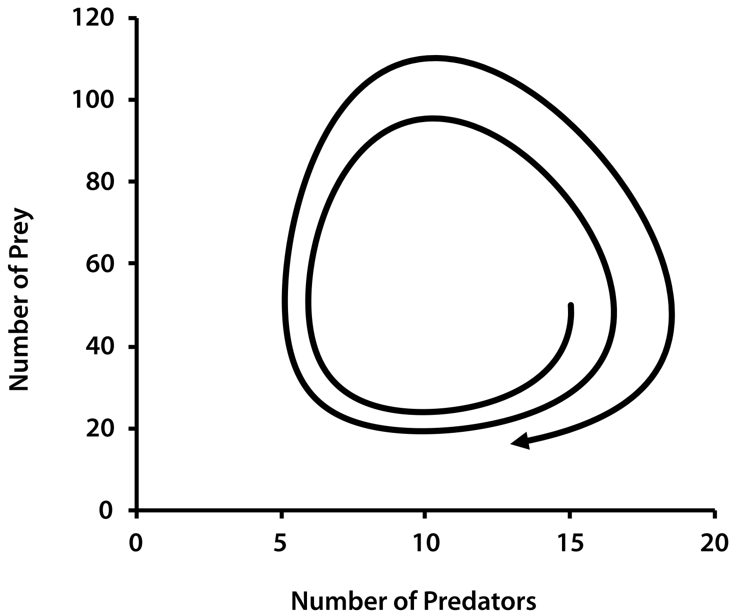


Figure 3. Example of predator-prey model. In this model, the initial conditions are N_0= 50 and P_0 =15. The model parameters used are a = 0.1, b = 0.01, c = 0.001, and d = 0.05.

Adaptation

The complex systems of interest in this analysis are adaptive. That is, they "change their behavior to improve their chances of survival or success—through learning or evolutionary processes."[33] This definition of adaptation implies the existence of a metric or metrics describing the relative fitness of elements in the system. Further, it implies some agency to effect the changes necessary for the system to adapt. This agency can be autonomic or created. The former might include evolutionary ecological systems in which the experimental agency exploring the space of possible biological designs is driven by factors such as genetic mutation and crossover in sexual reproduction. The selection mechanisms in such an autonomic system are usually some form of Tennyson's "Nature, red in tooth and claw."[34] Created technological systems are similar despite their physical, organizational, and legislative artifacts lacking an endogenous mechanism providing experimental/exploratory agency.[35] In this case, the role of selective agency is ascribed to people who—aside from

inventing, designing, and building systems—provide a feedback mechanism linking system performance and system goals (i.e., system fitness).[36]

Nonlinearity

Naïvely speaking, a linear system is one in which the behavior of the system is fully described as the sum of its parts.[37] Somewhat more formally, Edward Lorenz states, "A linear process is one in which, if a change in any variable at some initial time produces a change in the same or some other variable at some later time, twice as large a change at the same initial time will produce twice as large a change at the same later time. You can substitute 'half' or 'five times' or 'a hundred times' for 'twice,' and the description will remain valid."[38] That is, output is scaled to input in exactly the same way for all values. Both of these definitions are consistent with Descartes's reductionist worldview outlined previously.

Linearity is conceptually attractive for two fundamental reasons: many phenomena are approximately linear over some limited period or constrained domain,[39] and linear systems are subject to a wide variety of effective analytic methods.[40] In contrast, nonlinear systems or processes are simply those that are not linear, and this definition by negation extends to Lorenz's second observation: nonlinear systems have, for much of history, been considered nonsolvable.[41] Unfortunately, nonlinearity is ubiquitous. As noted in a statement attributed to the mathematician Stanislaw Ulam, "Using a term like nonlinear science is . . . like referring to the bulk of zoology as the study of non-elephant animals."[42]

One of the fundamental mechanisms through which nonlinearities arise is the circular interdependence described previously. This circularity or recursion—in which behavior of the system depends on the previous state of the system—need not involve diverse entities to produce nonlinear behaviors, however. Consider, for example, the logistic map, perhaps the canonical example of nonlinear complexity,

$$p_{t+1} = rp_t(1 - p_t),$$

where p_t gives the size of a population at time t (as a percentage of the carrying capacity of the environment), r describes the unrestricted (exponential) growth rate of the population, and the factor $1 - p_t$ expresses density-dependent mortality or starvation in the population and reduces the growth rate as the population approaches the carrying capacity of the environment.[43] The behavior of this system depends critically on the value of the growth parameter r, as shown in figure 4. For small values of r (less than 3.0), the population rapidly approaches

a steady equilibrium or limit point. For values of r between (approximately) 3.0 and 3.44949, the population settles into a periodic oscillation between $2 = 2^1$ distinct values. For values r between (approximately) 3.44949 and 3.54409, the population follows a periodic limit cycle defined by $4 = 2^2$ values. This pattern repeats, with the doubling of the limit cycles coming faster and faster until the behavior of the population becomes essentially chaotic.[44] In each of the first three cases shown, the behavior of the nonlinear system is well ordered and predictable—small perturbations in the initial conditions have little effect on long-run behavior. In the chaotic region, however, the trajectory that the population follows through time is qualitatively quite random and fills the space in the long run (as the number of limit points explodes). Also, small changes in initial conditions generate radically different long-range outcomes for the population.[45]

In figure 4, each of the first four plots show the trajectory that the logistic map follows when an initial condition of $p_0 = 3.0$ is applied and the various values for the parameter of r are given. These plots are usually referred to as web diagrams or cobweb plots and illustrate explicitly the recursive nature of the process (i.e., the output of one step becomes the input for the next). In each of the first three web diagrams, the limit points for the logistic map are shown as red dots; the trajectory of each plot and the limit points shown are not sensitive to small changes in the initial conditions. In the last spider plot, however, the parameter r is in the so-called chaotic region: the number of limit points has exploded (not shown), and the trajectory is "space filling." Also, as the last plot demonstrates, the behavior of the system is extraordinarily sensitive to very small changes in initial conditions. The logistic map and the properties illustrated here have been widely studied and described.[46]

This simple example for the study of nonlinear systems offers important lessons. First, seemingly random macroscopic behavior can emerge from deterministic processes; exogenous random inputs are not necessary to generate random behavior. This has implications that will be discussed in the next section. Second, long-term prediction may be impossible in some nonlinear systems—even in systems as simple as the logistic map. Significantly, however, this does not imply that all nonlinear systems are analytically intractable under all conditions, as some might claim. For example, Barry Watts and Williamson Murray indicate that "given . . . the degree to which military innovation in peacetime is unavoidably nonlinear, contingent, and infected with serendipity, it seems best to avoid generalizations in probing for answers."[47] This characterization of nonlinearity fails to acknowledge that while predicting or describing the details of system behavior may be problematic, elucidating and perhaps predicting higher-order behaviors are often possible in the most complex of nonlinear systems.[48] Finally, it is critical to note that while some

nonlinear systems can be treated as linear under certain circumstances, danger always exists in doing so. No linear system is capable of manifesting the phenomena shown in figure 4, and any linear approximation for such a system will fail to illuminate its critical characteristics.

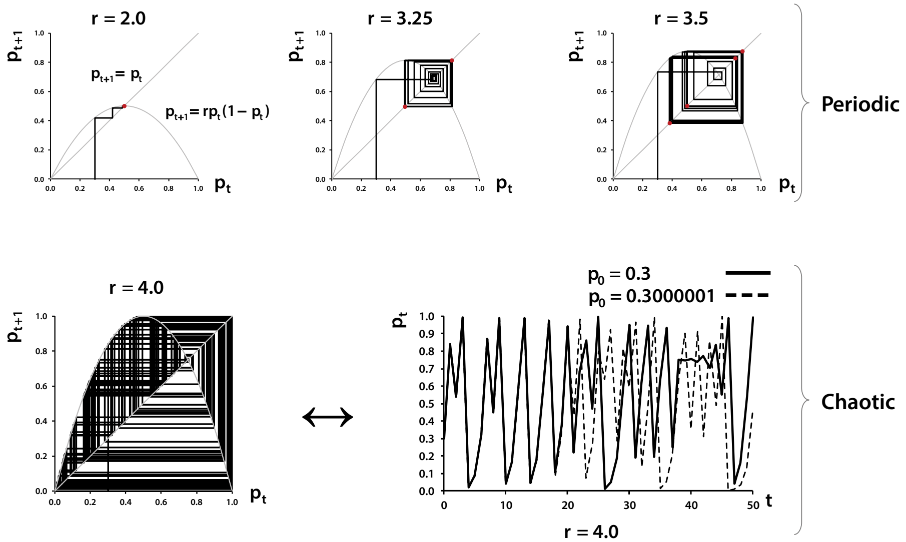


Figure 4. Logistic map behavior

In addition to these cautions, however, understanding the dynamics of nonlinear systems may also offer opportunities. For example, the possibility exists to exploit the disproportionate effects of small controlling perturbations of these systems to stabilize or direct their long-run behavior. Small corrections applied at the right moment and in the proper direction can profoundly influence nonlinear systems.[49]

Emergence

Yaneer Bar-Yam, president of the New England Complex Systems Institute, suggests that modern science remains in many ways trapped in the reductive paradigm that Descartes describes. Using the analogy of a forest, he claims,

> Most of science today has focused on the trees, studying the parts of a system, usually in isolation and ignoring higher-level phenomena. This approach creates barriers to the effective understanding of complex systems. However, focusing solely on the large scale

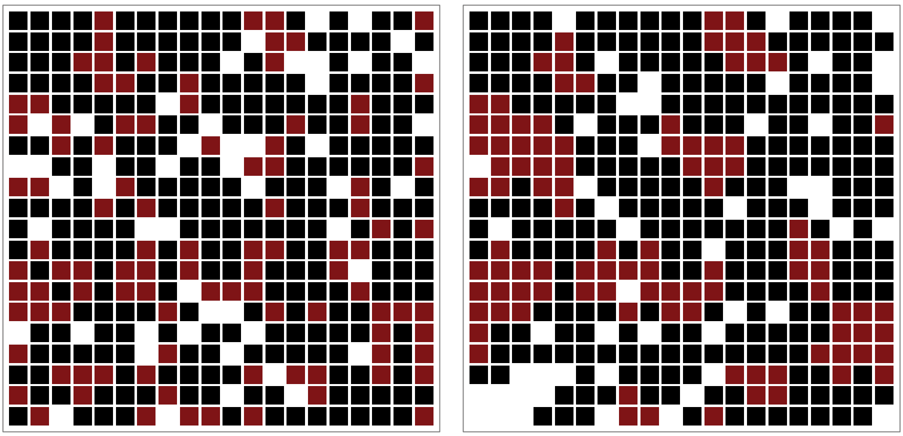
> view is not adequate. Anything the forest does as a whole is made up of the collective behaviors of the trees and the other plants and animals. Forest behaviors are collective; they are what parts of the system do together. Indeed, in many cases the behaviors are such that trees would not (or even could not) do them by themselves. In conventional views, the observer considers either the trees or the forest. Those whose zoom lens is focused on the trees consider the details to be essential and do not see the patterns that arise when considering trees in the context of the forest. Those who view the system from farther away, to observe the forest, do not see the details.[50]

In essence, the phenomenon of emergence captures the property of those systems in which, as Herbert Simon expresses, "the whole is more than the sum of the parts, not in an ultimate, metaphysical sense, but in the important pragmatic sense that, given the properties of the parts and the laws of their interaction, it is not a trivial matter to infer the properties of the whole."[51] These phenomena—the collective behaviors that are in some sense difficult to infer from the properties of the parts and their laws of interaction—are the emergent behaviors of interest in complex systems. As Bar-Yam states, the reductive approach to analyzing systems operates on the implicit belief that complex behavior at a given scale requires the operation of complex rules at that scale; it is this implicit belief that emergence explicitly rejects. Put another way, more is not simply more; more is different.[52]

Examples of emergent phenomena abound. Consider, for example, the Sugarscape model of Joshua Epstein and Robert Axtell. They populated a heterogeneous simulated environment (i.e., uneven resource distribution) with agents capable of movement who were looking for resources (sugar), consuming them, and accumulating them for later consumption. From this simple set of rules, a distribution of agent wealth following a Pareto distribution emerges: many agents in the system with few accumulated resources (wealth), a decreasing proportion of the population with a given level of accumulated savings as a function of the level of accumulated resources, and a few wealthy agents.[53] This distribution is an emergent property of the system; it is a macrolevel property of the system resulting or emerging from the collective interactions of individual agents. Epstein and Axtell expand this model by adding a second resource (spice) and allowing agents to trade among themselves for the two resources, resulting in the additional emergent phenomena of trade networks.[54]

A similar example is found in a model of segregation dynamics based on economist Thomas Schelling's analysis.[55] Again, consider a simulated landscape populated with simple agents, as shown in the initial state of figure 5.[56] Unlike the Sugarscape agents described above, in this case there are two types of agents, red and black; the red agents are in the minority here, comprising approximately 30 percent of the population. The agents are governed by two

impulses: sociability and homophily. During each turn, the agent inspects its neighborhood and counts the total number of agents in the neighborhood and the number of agents like itself. If the total number of agents falls below a sociability threshold, the agent will move to a randomly selected empty square. Similarly, if the total proportion of like agents in the neighborhood falls below a homophily threshold, the agent will move to a randomly selected empty square. In the example shown in figure 5, these sociability and homophily thresholds are the same for both agent types and set at 4.0 and 0.25, respectively. That is, each agent wants at least four neighbors and at least one in four to be of the same type as itself. Even with these quite tolerant conditions, the emergent distribution is relatively Balkanized. Importantly, this Balkanization is not a result of macrolevel behavior. That is, the simulation involves neither collusion among the agents nor a top-down mandate for separatism. As such, efforts to effect a change in the distribution must account for its origin in microbehaviors.[57]



Initial State (Uniformly Random) **Equilibrium State**

Figure 5. Model of segregation. The author developed this simulation in Visual Basic using Microsoft Excel.

Two additional examples that bear mention include the security dilemma and the Tragedy of the Commons. The security dilemma is summarized by political scientist John Herz. He observes a truth regarding the anarchic nature of human social conditions, that "a plurality of otherwise interconnected groups constitute ultimate units of political life, where groups live alongside

each other without being organized into a higher unity." He goes on to say that

> wherever such anarchic society has existed—and it has existed in most periods of known history on some level—there has arisen what may be called the "security dilemma" of men, or groups, or their leaders. Groups or individuals living in such a constellation [anarchic society] must be, and usually are, concerned about their security from being attacked, subjected, dominated, or annihilated by other groups and individuals. Striving to attain security from such attack, they are driven to acquire more and more power in order to escape the impact of the power of others. This, in turn, renders the others more insecure and compels them to prepare for the worst. Since none can ever feel entirely secure in such a world of competing units, power competition ensues, and the vicious circle of security and power accumulation is on.[58]

Just as the actors in the security dilemma, spurred by locally rational action at the individual level, produce a macrolevel behavior with potentially disadvantageous results for the individual actors, actors in the so-called Tragedy of the Commons can induce macro ruin through acts of microrationality. Garret Hardin describes the "Tragedy" as a problem arising from the collectivization of costs spread across a population of herdsmen and individualized gains accruing to individuals whenever they add animals to their herds. In this logic, "each man is locked into a system that compels him to increase his herd without limit—in a world that is limited."[59] Through rational action at the individual (micro) level, the system is led to ruin at the macrolevel. Notice that in each of these examples, the macrolevel outcome is a function of the interaction of multiple agents; these outcomes can emerge only in an environment with multiple actors.

Each of the examples of emergence presented here is, after the fact, perfectly explicable. While a priori inference of Simon's "properties of the whole" is not trivial, it is possible, and the mechanisms connecting microbehavior and macrophenomena are understandable. This is not necessarily the case in every example of emergent behavior. Scholars studying complex systems often distinguish between two categories of emergence: weak and strong. Weak emergence "describes the difficult to understand micro-to-macro relationship between microscopic parts and their interactions with each other, and their collective macroscopic behavior," whereas strong emergence "describes properties that are unique to the collective—cannot be identified through any observations of the parts, and is counter to the conventional perspective that parts determine the behavior of the whole."[60] Each of the examples of emergence presented in this paper is located on a continuum between weak (perfectly trivial) and strong (perfectly intractable). The last two characteristics discussed here—coevolution and path dependence—are emergent phenomena.

Coevolution

The modern conception of evolutionary theory—originally derived from the observation of biological systems—characterizes evolution as "an algorithm; it is an all-purpose formula for innovation, a formula that, through its special brand of trial and error, creates new designs and solves difficult problems."[61] As a general method for searching an enormous collection of possibilities, a "design space," for solutions—in biology, the collection of possible genetic sequences and survivable or fit organisms—evolution can be extraordinarily effective. Evolutionary or genetic algorithms simultaneously employ a parallel search method; a combination of exploitative and explorative experimentation; and continuous, recursive innovation in searching the design space.[62] The earliest use of such algorithms as a means for solving an engineering problem is their application to the task of optimizing parameters for wing design.[63] This formulation—assessing potential design parameters for an airfoil—involves the evaluation of alternative solution strategies against a fixed set of design criteria (e.g., cost, lift, weight, drag, etc.). That is, an organism in this example (the airfoil) is evolving a strategy (genetically or otherwise) to optimize its fitness within the context of a fixed environment.

In biological and social systems, however, the environment is rarely fixed in every respect. In these systems, each strategy for action or genotype takes as its environment both exogenous factors (e.g., in a biological system these might include geography, weather, etc.) that remain fixed relative to the strategy and endogenous factors (e.g., the collection of all other strategies in the system). Thus, in such a system a change in one fitness strategy has the potential to affect the evaluation of fitness for the other strategies.[64] For example, in a biological predator-prey relationship, increased speed in a predator may make evasion a less attractive strategy for a prey species, leading to selection forces emphasizing camouflage. A change in the predator alters the characterization of fitness for the prey. This development of camouflage may, in turn, elevate the importance of eyesight to the predator species, and so on. This mutual, interactive effect on the respective fitness evaluation of individual strategies in the system is called coevolution and makes optimality a moving target.[65] A more colorful description of the phenomenon is the "Red Queen" principle,[66] so named for the Lewis Carroll character who tells Alice, "Now, here, you see, it takes all the running you can do, to keep in the same place. If you want to get somewhere else, you must run at least twice as fast as that!"[67]

A more detailed example examining a simulation of evolutionary strategies for playing an iterated "Prisoner's Dilemma"—based on a synthesis of work by Robert Axelrod and the physicist Kristian Lindgren—should clarify

the criticality of considering the coevolutionary aspect of complex adaptive systems.[68] In the Prisoner's Dilemma, each of two players is offered two options: cooperate or defect.[69] Their choices lead to four outcomes with associated benefits for each player (see table 1).

Table 1. The Prisoner's Dilemma

		Player Two	
		Cooperate	Defect
Player One	Cooperate	$R = 3$, $R = 3$ Reward for mutual cooperation	$S = 0$, $T = 5$ Sucker's payoff and temptation to defect
	Defect	$T = 5$, $S = 0$ Temptation to defect and sucker's payoff	$P = 1$, $P = 1$ Punishment for mutual defection

Adapted from Robert Axelrod, *The Evolution of Cooperation* (New York: Basic Books, 2006), 8. Payoffs for player one are listed first. The Prisoner's Dilemma is characterized by ordering the payoffs, shown as $T > R > P > S$, and by requiring $R > (T + S) / 2$. The specific values shown are used for illustration and simulation, but any values satisfying these relations define a Prisoner's Dilemma (ibid., 206).

To illustrate the coevolutionary behavior of players competing under the payoff rules described for this game, a simulation was developed. To initialize the simulation, randomly generated strategies—each capable of acting on a memory of one game turn and a default initial play—were placed in an artificial landscape.[70] This landscape is such that each location contains a single player/strategy for playing the Prisoner's Dilemma and is adjacent to six locations containing players with whom the player will compete.[71]

In each generation, players compete against their neighbors according to the strategies encoded in their respective genotypes.[72] Each player is then replaced by the member of its neighborhood (comprised of its six neighbors and a copy of itself) with the best average score across the games played in the current generation.[73] The replacement/reproduction involves the potential for mutation/evolution. Three types of evolution are incorporated in the simulation: (1) gene duplication, doubling the memory available to the strategy; (2) split mutation, reducing by half (chosen randomly) the memory available to the strategy; and (3) point mutation, changing the strategy's response to a given history from cooperation to defection, or vice versa.[74]

The results from one run of this simulation are shown in figure 6. Each curve in the plot charts the proportion of the simulation landscape occupied by a given strategic genotype.[75] Even a cursory examination of the results reveals several outcomes worthy of note. First, the tit-for-tat strategy (cooperate

on the initial move and thereafter repeat the move of the opposing player) made famous as the winner of Axelrod's computer tournaments is shown in red.[76] Early in the simulation, this strategy is reasonably successful, comprising approximately 30 percent of the total population for approximately 100 generations between generations 50 and 150 (with substantial variability). After this brief period of relative success, however, tit for tat is dominated and eventually completely eliminated by other strategies in the population. As successful as tit for tat is in the early generations of the simulation, a closely related strategy (cooperate on the initial move and thereafter only if both players cooperated on the previous turn) is approximately twice as successful and more stable in its population dominance. This strategy, shown in blue, might best be described as "cooperate but punish." Regardless of the factors of behavior and geography that allowed this strategy to dominate the early generations of the simulation, this dominance is transitory; by generation 500 it has disappeared from the population.[77] The strategy shown in black is identical to cooperate but punish except that it begins each competition by alternating between cooperation and defection.[78] This strategy—call it cooperate-defect—can only be more successful than cooperate but punish because the other strategies in the population give it an advantage.[79] This strategy also disappears from the population; a long period of 200 generations follows in which no strategy achieves a significant degree of dominance. Eventually, a more complicated strategy (with a memory of two turns) achieves some dominance near the end of the scenario (shown in brown). This strategy is programmed to respond cooperatively to only five of 16 (31.25 percent) scenarios with which it might be faced. Notice that cooperative behavior is not unambiguously positive in terms of strategic fitness. Also, the almost immediate decline experienced by this strategy is associated with a point mutation in one of its members making the resultant strategy *less* cooperative.

The particular strategies shown in figure 6 and their association with cooperative and defective behaviors in a real ecological or social system are not the point here. Rather, the lesson is that in coevolutionary systems no single strategy is likely to act as a panacea for the competitive environment. Reliably describing universal normative principles for effective strategies—as Axelrod attempts—is likely to be difficult.[80] Strategies that operate effectively in a given time and place are dependent on others for their effectiveness. Since strategies are a critical element of the environment, it changes as they evolve to keep pace with the fitness landscape in motion.

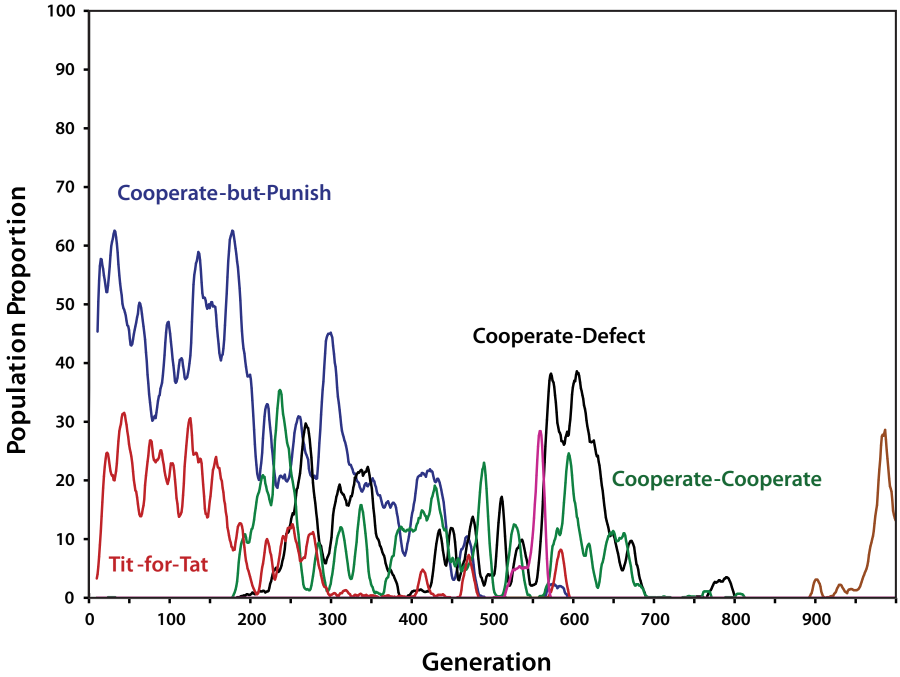


Figure 6. Iterated Prisoner's Dilemma in a coevolutionary strategic landscape. The actual population proportion for each strategy is not displayed to maximize the chart's clarity. The curves shown are 10-step moving averages of the proportion of the population comprised by each strategy. The author developed this simulation in Visual Basic using Microsoft Excel.

Path Dependence

The final behavioral characteristic of complex adaptive systems is a phenomenon usually referred to as path dependence.[81] Beinhocker describes the traditional paradigm of economics—"the set of concepts and theories articulated in undergraduate and intermediate graduate textbooks" and "the concepts and theories that peer-reviewed surveys claim, or assume, that the field generally agrees on"—as being dominated by "notions of rational, optimizing consumers and producers, and (with the exception of investments in technology) those choices being bound by decreasing returns."[82] A consequence of this negative feedback paradigm is the notion that an economic system's history has little or no influence on its future. Rather, economist Brian Arthur observes that "conventional economics texts have tended to portray the economy

as something akin to a large Newtonian system, with a unique equilibrium solution preordained by patterns of mineral resources, geography, population, consumer tastes, and technological possibilities." In this view, history "merely delivers the economy to its inevitable equilibrium."[83] If one admits the efficacy of positive feedback mechanisms, however—mechanisms with parallels in numerous nonlinear physical systems—then economic (and other complex) systems operate differently.

First and foremost, such systems admit the possibility of multiple equilibria and historical trajectories leading to divergent equilibria not always themselves widely divergent. Thus, in these systems, small perturbations at critical junctures, accidents of history, and the influence of chance can affect the course of history.[84] Then, once these events tip the course of history in a given direction, positive feedback and increasing returns may cause the path selected to become locked in and difficult to escape, even if the given outcome is not a global optimum.[85]

An interesting example of path dependence is found in the nonrational behavior exhibited by human beings who, as decision agents for force-structure evolution, close "the feedback loop between system performance and system goals and in so doing correct errors in system performance."[86] That humans do not behave with perfect economic rationality is a well-established fact,[87] but one particular manifestation of human irrationality is of interest with respect to the property of path dependence in force structure: *arbitrary coherence*. In economics, the principle of arbitrary coherence connotes the fact that "although initial prices . . . are 'arbitrary,' once those prices are established in our minds they will shape not only present prices but also future prices (this makes them 'coherent')."[88] This influence is not limited to pricing. The same principles lead to other self-reinforcing, persistent behaviors (or habits) in humans.[89]

Such dynamics are important in created complex systems such as the technological systems described above. Choices made early in the development of a technology—to follow a path with immediate short-term value at the expense of ignoring a slowly developing technology with greater long-term potential, for example—may drive development toward suboptimal solutions. For instance, Robert Jervis describes how the alliances formed led to the First World War and mutually reinforcing behaviors contributed to the Second. Also, Stathis Kalyvas recounts vicious and virtuous cycles of violence and nonviolence in the Greek Civil War.[90]

Notes

1. Of course, the assertion that one can do so is taken on faith.
2. Descartes, *Discourse on Method*, 17.
3. Bousquet and Curtis, "Beyond Models and Metaphors," 43–62.
4. *Merriam-Webster's Collegiate Dictionary*, 11th ed., s.v. "analysis."
5. Laplace, *Philosophical Essay on Probabilities*, 3–4.
6. Poincaré, *Foundations of Science*, 397–98.
7. Ibid., 398.
8. Gleick, *Chaos*, 11–31. In some cases, the described indeterminacy is not driven by the finite capacity of the observer, as Poincaré and Lorenz indicate. For example, one of the fundamental characteristics of quantum mechanics, the Heisenberg Uncertainty Principle, states that it is not possible to determine with precision both the position and momentum of a subatomic particle (specifically of a photon). More precisely, the product of the measurement errors in these two quantities is proportional to Planck's constant, so increasing precision in one measurement must necessarily decrease precision in the other. Thus, even if every particle in a system could be observed, the Heisenberg Uncertainly Principle implies that the form of indeterminacy Poincaré describes must be present in the system. For a general characterization of the Uncertainty Principle, especially as it relates to strategy, see Dolman, *Pure Strategy*, 99. For a somewhat more technical characterization, see Hilgevoord and Uffink, "Uncertainty Principle."
9. Waldrop, *Complexity*, 9–13.
10. Walby, "Complexity Theory," 449–70.
11. Lloyd, "Measures of Complexity," 7–8.
12. Page, *Diversity and Complexity*, 25.
13. Mitchell, *Complexity*, 13.
14. *Merriam-Webster's Collegiate Dictionary*, 11th ed., s.v. "diverse."
15. Page, *Diversity and Complexity*, 14.
16. Ibid., 55. Page includes a third category: diversity of community composition. The categories addressed in this analysis are sufficient to motivate the issue of diversity as it relates to the US Air Force and the problem of force-structure analysis.
17. Ibid., 64–66.
18. Alfréd Rényi offered a variation on this formula in 1961 as a generalization of Shannon entropy in "On Measures of Entropy and Information," 547–61.
19. Hirschman, "Paternity of an Index," 761; and Simpson, "Measurement of Diversity," 688. Technically, if n_i is the number of the ith type in a population and $N = \Sigma n_i$, then Simpson's index is $\Sigma n_i(n_i - 1)/(N^2 - N)$. This quantity is an unbiased estimator for Σp_i^2, where $p_i = \frac{n_i}{N}$. Simpson, "Measurement of Diversity," 688.
20. Page, *Diversity and Complexity*, 66–70.
21. Further discussion of the relationship between entropy and various measures of diversity can be found in Hill, "Diversity and Evenness," 427–32; and Jost, "Entropy and Diversity," 363–75.
22. There are any number of possibilities for calculating the distance between two points in space. For example, given two points (x_1, y_1) and (x_2, y_2) in the Cartesian plane, the Euclidean distance between the points is given by $\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$. This traditional concept of geometric distance—sometimes called the 2-norm distance—generalizes to a quantity called a p-norm, but all of these generalizations rely on the point lying in Euclidean space; they do not extend to objects described non-numerically.

23. Weitzman, “On Diversity,” 363–405.

24. An alternative and equally general concept of distance applicable to a problem of this type is the so-called Hamming distance, named for the mathematician Richard Hamming who first described the metric in 1950. In considering a binary string of length *n*, Hamming defined the distance between two such strings as the number of positions at which the two strings differ. So if a binary encoding exists describing each element in a population, one can readily describe a distance between them. See Hamming, “Error Detecting and Error Correcting Codes,” 147–60. This distance can be generalized to nonbinary or alphabetic strings by ignoring the alphabet character used, simply counting the absolute number of changes necessary to transform one string into the other, and disregarding the extremity of those changes.

25. The characterization of the diversity metric as the sum of the lengths of the branches on the taxonomic tree is informal. For a more formal definition of the metric, see Weitzman, “On Diversity,” 363–405. For a procedural description of the computation of this metric, see Page, *Diversity and Complexity*, 72–73. The Weitzman diversity of the population described by the taxonomic tree in figure 1 is eight.

26. The amount added to the count of the effective number of species will depend on the scale of the differences between the species (i.e., their distance from one another). Solow and Polasky first proposed this idea in “Measuring Biological Diversity,” 95–103. Additional mathematical work on their proposal appears in Leinster’s articles “Magnitude of Metric Spaces” and “Maximum Entropy Theorem.”

27. For further discussion of the concept of the effective number of species as a measure of diversity and the relationship of this measure to other measures of diversity, see Tuomisto, “Consistent Terminology for Quantifying Species Diversity?,” 853–60, and “Diversity of Beta Diversities,” pts. 1 and 2, 2–45.

28. Page, *Diversity and Complexity*, 73–76.

29. This implicitly assumes that the prey species has an unlimited food source and suffers no effects of crowding and that the predator species is entirely dependent on the prey species for its sustenance.

30. A more formal representation is given by the coupled, first-order, nonlinear differential equations $\frac{dN}{dt} = aN - bNP$ and $\frac{dP}{dt} = cNP - dP$. In these equations, *N* and *P* are the populations of the prey and predator, *a* and *d* are their associated per capita rates of change independent of the other species, and *b* and *c* are their rates of change due to interaction. These equations were first studied (independently) by Alfred Lotka and Vito Volterra in the 1920s and have been studied extensively since. See Berryman, “Origins and Evolution of Predator-Prey Theory,” 1530–35.

31. Arthur, “Inductive Reasoning and Bounded Rationality,” 406–11. In another exploration of this phenomenon of interdependent expectations on the behavior of agents, Arthur analyzes the formation of stock market prices in his articles “Complexity in Economic and Financial Markets,” 20–25, and “Complexity and the Economy,” 107–9.

32. Beinhocker, *Origin of Wealth*, 124.

33. Mitchell, *Complexity*, 13.

34. Tennyson, *In Memoriam A. H. H.*, canto LVI, line 15. Note that while the interdependencies illustrated in the predator-prey model operate on this same principle, they do not indicate an adaptive system except in the loosest sense of the word. The sizes of the populations adapt, in a sense, to the available resources, but the agents themselves (predators and prey) and the parameters defining their relationships are static.

35. This characterization of the artifacts in a technological system is taken from Hughes, “Evolution of Large Technological Systems,” 51.

36. Ibid., 54.

37. Mitchell, *Complexity*, 22.

38. Lorenz, *Essence of Chaos*, 161. These definitions are essentially equivalent in that either can be considered a consequence of the other.

39. Herbert A. Simon refers to such systems as nearly decomposable. The nonlinearities emerge from interaction of system entities—either with themselves or with others—and if the level of interaction is sufficiently weak (but not negligible), they may be treated as nearly decomposable. Simon denotes two characteristics of nearly decomposable systems similar to those expressed by Lorenz: (1) the short-run behavior of each system element is approximately independent of the short-run behavior of the other system elements (this leads to the proportionality Lorenz describes); and (2) the long-run behavior of any one element depends on the behavior of the other elements only in the aggregate. Simon's canonical example is of temperature regulation in a well-insulated building divided into rooms (elements) separated by imperfectly insulated walls. See Simon, "Architecture of Complexity," 473–77.

40. Lorenz, *Essence of Chaos*, 162.

41. Campbell et al., "Experimental Mathematics," 374–84.

42. Ibid., 374.

43. Pierre François Verhulst first described this mathematical model of Malthusian population dynamics in 1838. See Berryman, "Origins and Evolution of Predator-Prey Theory," 1530. It was later popularized by the biologist Robert May, who studied the dynamics of the relation in his article "Simple Mathematical Models with Very Complicated Dynamics," 459–67.

44. The rate at which the doubling occurs in the logistic map is governed by the so-called Feigenbaum constant, $\delta \approx 4.669201609103$, first described by physicist Mitchell Feigenbaum. This doubling behavior is seen in a broad array of recursively defined relations. See Feigenbaum, "Quantitative Universality for a Class of Nonlinear Transformations," 25–52.

45. For a precise mathematical characterization of chaotic systems and an examination of the conditions given here, see Hasselblatt and Katok, *First Course in Dynamics*, 205–10.

46. For example, see Gleick, *Chaos*, 59–80; Mitchell, *Complexity*, 27–38; or Vivaldi, "Experiment with Mathematics," 33–43.

47. Johnson, *Fast Tanks and Heavy Bombers*, 15.

48. Mitchell, *Complexity*, 38.

49. For descriptions of theoretical developments in this area, see Ott, Grebogi, and Yorke, "Controlling Chaos," 1196–99; or Romeiras et al., "Controlling Chaotic Dynamical Systems," 165–92. A particularly interesting application of this form of control is seen in the so-called space transport network, a dense collection of trajectories connecting libration points in the solar system. See Ross, "Interplanetary Transport Network," 230–37.

50. Bar-Yam, *Making Things Work*, 27.

51. Simon, "Architecture of Complexity," 468.

52. Anderson, "More Is Different," 393–96.

53. Epstein and Axtell, *Growing Artificial Societies*, 21–53. Pareto distributions and power laws are common in many physical and social systems. For an overview of these systems, see Newman, "Power Laws," 323–51; or Clauset, Shalizi, and Newman, "Power-Law Distributions," 661–703.

54. Epstein and Axtell, *Growing Artificial Societies*, 94–137.

55. Schelling's model is one-dimensional, with neighborhoods of an agent comprised of the agents to the left and right out to some distance. A two-dimensional space is used here for visual clarity. Schelling, "Models of Segregation," 488–93.

56. On this landscape, the neighborhood of each agent consists of the eight squares surrounding it. Points on the edge of the square are considered adjacent to points on the opposite edge in the natural way. In this toroid or doughnut-shaped world, each neighbor has precisely eight neighboring points that may be occupied by an agent or not.

57. Of interest, in social systems involving ethnic divisions among agents, the less-than-radical segregation illustrated here can generate conditions conducive to ethnic violence along the seams between social groups. See Lim, Metzler, and Bar-Yam, "Global Pattern Formation and Ethnic/Cultural Violence,"1540–44; and Rutherford et al., "Good Fences."

58. Herz, "Idealist Internationalism and the Security Dilemma," 157.

59. Hardin, "Tragedy of the Commons," 1243–48. See also Olson, *Logic of Collective Action*.

60. Bar-Yam, "Mathematical Theory of Strong Emergence," 15–24.

61. Beinhocker, *Origin of Wealth*, 12.

62. Ibid., 213–16.

63. Mitchell, *Introduction to Genetic Algorithms*, 2.

64. Coevolution is an emergent behavioral phenomenon associated with complex adaptive systems resulting from the interdependent nature of the system elements and their capacity for adaptation. Removing either aspect of the system (i.e., enforcing independence or limiting the capacity for adaptation) eliminates the phenomenon of coevolution.

65. Beinhocker, *Origin of Wealth*, 201.

66. Leigh Van Valen coined the term in this context in his article "New Evolutionary Law," 1–30.

67. Carroll, *Through the Looking Glass*, 39.

68. See Axelrod's *Evolution of Cooperation* and "Evolution of Strategies in the Iterated Prisoner's Dilemma," 32–41; and Lindgren, "Evolutionary Phenomena in Simple Dynamics," 295–312.

69. The Prisoner's Dilemma is based on this scenario: The district attorney offers the two prisoners, codefendants in a criminal case, the following deal: if neither confesses (that is, the two "cooperate"), the district attorney will be able to convict both only on a lesser charge, and each will receive a relatively brief jail term (the "mutual reward" outcome); if one prisoner confesses ("defects") and the other does not, the former will be released [the "temptation"] and the latter (the "sucker" or "saint") will be harshly sentenced; if both confess, each will be sentenced more harshly than if neither confessed but less harshly than if only one had done so (the "mutual punishment" outcome). The district attorney does not allow the prisoners to communicate with each other and requires each prisoner to choose only once in ignorance of the other's choice. Gowa, "Anarchy, Egoism, and Third Images," 167–86.

70. The use of artificial landscape is one deviation from Axelrod's experiments with genetic algorithms, and coevolutionary play of the Prisoner's Dilemma as geography is not a consideration in his evolutionary experiments. Axelrod, "Evolution of Strategies in the Iterated Prisoner's Dilemma," 32–41.

71. At the boundary of a flat-earth simulation landscape, players/strategies compete against fewer than six opponents in each generation. In incorporating local geographic consideration into the simulation, this work follows the example of Lindgren. This implementation differs from that of Lindgren, however, in two ways. First, Lindgren's geography is defined by a square lattice in which each player/strategy is adjacent to four competitors. Second, Lindgren's landscape is a torus, with opposite edges considered adjacent in the natural way. In this way, every player is adjacent to exactly four neighboring competitors. Lindgren, "Evolutionary Phenomena in Simple Dynamics," 295–312.

72. Each game played has 80–120 iterations of the Prisoner's Dilemma (chosen from a uniformly random distribution). This serves two functions: (1) it prevents the evolution of

strategies to exploit a known duration of play, and (2) it introduces an element of noise representative of exogenous environmental factors.

73. In the event of a tie, the winner is selected randomly from among those tied for the best score.

74. Reproduction in this context is asexual and does not include the potential for crossover mutation. This differs from the evolutionary algorithm employed in Axelrod, "Evolution of Strategies in the Iterated Prisoner's Dilemma," 32–41, but the described mutations are similar to those used in Lindgren, "Evolutionary Phenomena in Simple Dynamics," 295–312. The mutation rate in the simulation induces (on average) five point mutations per generation and (on average) one of each other type (duplication and split) every 20 generations.

75. For clarity, the results for only the five most successful strategies are shown. Over the course of 1,000 generations, the simulation produced 1,890 distinct strategic genotypes.

76. Axelrod, *Evolution of Cooperation*, 27–54.

77. An isolated pocket of this strategy reappears briefly between generation 550 and 600.

78. Technically, the default defection will not actually ever be played. Since the strategy carries only a memory of one turn, its subsequent play is determined by its initial play and the play of the opponent. Where the default defection is important is in seeding the memory—and determining the initial play—of an opponent with a memory longer than one turn. This allows the strategy to exploit a set of strategies in the population that seek to induce reconciliation by responding to a cooperation-defection history (or a single defection) with some degree of cooperation.

79. The strategy shown in green is identical to cooperate-defect (black) except that it has a default strategy of cooperation-cooperation to initiate play. In a sense, then, its phenotype (behavior) is functionally equivalent to that of cooperate-but-punish. It is this strategy—call it cooperate-cooperate—that enabled the emergence of cooperate-defect via a point mutation at generation 187.

80. Axelrod, *Evolution of Cooperation*, 109–41.

81. Scott Page distinguishes among three forms of path dependence. Simple path dependence describes the effect of history on the present and future in those cases where the events and the order of those events relative to one another are determinative. State dependence, the second of Page's types, describes a dependence on history described by a Markov process; that is, the next future state—from among finitely many such states—depends on the previous state. The third type, whimsically referred to as "phat dependence," describes those cases in which past events are determinative, but their order does not matter. Page points out that outcomes in the Pólya process often used to describe the mechanisms of path dependence depend only on the distribution of past events and not on their order. See Page, "Essay: Path Dependence," 87–115. For the purposes of this discussion, however, the more naïve characterization used here is sufficient.

82. Beinhocker, *Origin of Wealth*, 24, 43.

83. Arthur, "Positive Feedbacks in the Economy," 99.

84. Note the parallel between this aspect of path dependence and the opportunity for control of chaotic nonlinear systems described above.

85. Arthur, "Positive Feedbacks in the Economy," 92.

86. In this context, the terms *rational* and *nonrational* are used in the economic sense. Herbert Simon cogently summarizes the assumptions regarding rationality:

> Traditional economic theory postulates an "economic man," who, in the course of being "economic" is also "rational." This man is assumed to have knowledge of the relevant aspects of his environment which, if not absolutely complete, is at least impressively

> clear and voluminous. He is assumed also to have a well-organized and stable system of preferences, and a skill in computation that enables him to calculate, for the alternative course of action that are available to him, which of these will permit him to reach the highest attainable point on his preference scale.

Simon, "Behavioral Model of Rational Choice," 99. See also Hughes, "Evolution of Large Technological Systems," 54.

87. For example, see Ariely's *Predictably Irrational* and *Upside of Irrationality*; Chabris and Simons, *Invisible Gorilla*; Gilbert, "How Mental Systems Believe," 107–19; Guth, Scmittberger, and Schwarze, "Experimental Analysis of Ultimatum Bargaining," 367–88; Kahneman, Knetsch, and Thaeler, "Experimental Test of the Endowment Effect," 1325–48; Kahneman and Tversky, "Prospect Theory," 263–92; Shubik, "Dollar Auction Game," 109–11; and Tversky and Kahneman, "Judgment under Uncertainty," 1124–31. While far from complete, this list gives a sense of the depth and breadth of evidence (empirical and theoretical) against the assumptions of economic (and more general) rationality in human cognition and behavior.

88. Ariely, *Predictably Irrational*, 28.

89. Ibid., 25–53.

90. Jervis, *System Effects*, 55, 245–52. Of note, in this context Jervis states that "because actions change the environments in which they operate, identical but later behavior does not produce identical results. Indeed, history is about the changes produced by previous thought and action as people and organizations confront each other through time." As discussed previously, the analytic categories describing characteristics and behaviors of complex adaptive systems are not mutually exclusive. Jervis's characterization of path dependence, for example, strays into both interdependence and coevolution. See also Kalyvas, *Logic of Violence in Civil War*, 302–7.

Chapter 3

Is a Force Structure a Complex Adaptive System?

The *Department of Defense Dictionary of Military and Associated Terms* defines *force structure* (one of the major components of military capability) as "numbers, size, and composition of the units that comprise US defense forces; e.g., divisions, ships, air wings."[1] Generally included under this heading are such factors as personnel, equipment, organization and hierarchy, and command relationships. Consider, for example, the most recent *Quadrennial Defense Review* (*QDR*), a congressionally mandated "comprehensive examination of the national defense strategy, force structure, force modernization plans, infrastructure, budget plan, and other elements of the defense program and policies of the United States."[2] The *QDR* describes the force structure for the Air Force in terms of wing equivalents and an approximate number of primary mission aircraft in the total force.[3] Characterizing the Air Force in terms of wings, however, implicitly encompasses the personnel (headquarters, operations, and support) and speaks directly to the organizing concept of the Air Force. This analysis presents an appreciably circumscribed notion of force structure, limiting the focus to material programs and especially to primary mission aircraft.

Limiting the scope of a force structure in this way presents an obvious methodological concern. Specifically, it simplifies the system under investigation substantially and implicitly eliminates—or at least markedly constrains—consideration of two entire USAF core functions (space superiority and cyberspace superiority). It may also tend to tacitly marginalize at least two others (building partnerships and agile combat support).[4] If it can be shown, however, that this circumscribed force structure is a complex adaptive system in the sense detailed in chapter 2, the more comprehensive conception of force structure will only add to that complexity. So while the proposed narrowing of the concept of force structure may appear reductionist and seem to contradict the overall purpose of this analysis in understanding force structures as complex systems, the logic of the overall argument is not compromised by the simplification.

The next natural question—indeed, the central question of this investigation—is whether or not the force structure of the Air Force as defined here is a complex adaptive system. Recall the definition of a *complex adaptive system* developed in chapter 2: a system comprised of diverse, interdependent, adaptive elements interacting nonlinearly and exhibiting systemic behaviors including

emergence, coevolution, and path dependence across multiple scales. It is on this definition—and a heuristic argument that the force structure of the Air Force satisfies this definition—that the following discussion centers.[5]

Two points of explanation regarding the use of the term *heuristic* and the overlap in the heuristic categories comprising the definition of a complex adaptive system are first warranted. A procedure is described as heuristic if it "involve[s] or serv[es] as an aid to learning, discovery, or problem-solving by experimental and especially trial-and-error methods."[6] The argument detailed below is heuristic in that it shows how a force structure is a complex adaptive system by addressing each component of the definition separately and demonstrating that the stated elements or behaviors are either observed in or exhibited by a force structure.

This raises the issue of overlap in the components of the definition of *heuristic*: the categorical components of the definition are not mutually exclusive. In fact, the relationship among components is tautological in some cases. For example, the characteristics of interdependence and adaptability describe a complex adaptive system in terms of what it is, while the behavior of coevolution describes what a complex adaptive system does. Interdependence and adaptability, however, are necessary and sufficient conditions for a system to exhibit coevolutionary behavior. Similarly, a principal source for nonlinear behaviors in complex adaptive systems is the inherent interdependence of those systems. As such, many of the examples given will overlap one another.

That the USAF force structure exhibits the enumerated characteristics and behaviors of complex adaptive systems is, in some sense, self-evident. The philosopher of Napoleonic war, Antoine-Henry Baron de Jomini, faced a similar conundrum and argued that while the concentration of force on decisive points is the "one great principle underlying all the operations of war . . . [,] it would be little short of ridiculous to enunciate such a principle without accompanying it with all the necessary explanations for its application."[7] For our purposes, it is likewise worth exploring some of the particular manifestations and measures for these phenomena in parallel with the descriptions in chapter 2.[8]

Diversity

The last characterization of diversity across types discussed in the previous chapter was an indicator of the diversity of attributes present in the system under examination. One recognizable collection of high-level attributes the Air Force uses to distinguish platforms within its force structure has been mentioned: the 12 Air Force core functions.[9] Table 2 shows the correspondence between these functions and the various platforms that comprise the

force structure designed to fill those core functions.[10] Based on this information, the attribute diversity for the Air Force's aircraft-centered force structure would be 10. As presented, of course, the attribute/platform pairings are quite discrete, and the correspondence between core functions and platforms is one to one.[11] This categorization does not perfectly capture the attributes of each aircraft type, however. For example, an F-15E or an F-16C/D is capable of performing in both an air-superiority and an attack role,[12] a B-52 or a B-2 may carry conventional weapons as well as nuclear weapons,[13] and command-and-control (C2) platforms such as the E-3 Airborne Warning and Control System (AWACS) and E-8 Joint Surveillance Target Attack Radar System (JSTARS) provide both C2 and surveillance and reconnaissance functionality.[14]

Table 2. Air Force core functions and aircraft matrix

Air Force core function[a]	Aircraft type(s)
Nuclear deterrence ops	B-2, B-52
Global precision attack	A-10, B-1, F-15E, F-16C/D, F-35A
Air superiority	F-15C/D, F-22
Rapid global mobility	C-12, C-130E/H/J, C-17, C-20, C-21, C-27, C-32, C-37, C-38A, C-40, C-5, C-9, KC-10, KC-135, VC-25
Global integrated ISR	MC-12, MQ-1, MQ-9, RC-135, RC-26, RQ-170, RQ-4, U-2, WC-130H/J, WC-135
Command and control	E-3 AWACS, E-4 NACP, E-8 JSTARS
Special operations	AC-130H, CV-22, EC-130E, EC-130J, MC-130E/H, MC-130H, MC-130J, MC-130W
Personnel recovery	HC-130J, HC-130P/N
Building partnerships	LAAR, LiMA[b]
Agile combat support	T-1, T-38, T-6

The assignment of aircraft types to Air Force core functions is from Headquarters United States Air Force, "Air Force 30-Year Aviation Procurement Report Data Submission," 10 November 2010.

[a] Note that space superiority and cyberspace superiority are core functions without aircraft platforms designated against them. As previously indicated, the tightly constrained definition of force structure used here will tend to implicitly and explicitly eliminate consideration of certain force structure elements.

[b] Light attack / armed reconnaissance (LAAR) and light mobility aircraft (LiMA). According to the Fiscal Year 2013 Air Force Posture Statement, "Due to Fiscal constraints, the Air Force terminated the Light Attack Armed Reconnaissance and Light Mobility Aircraft programs." Department of the Air Force, Fiscal Year 2013 Air Force Posture, 24. The platforms are included in this table to remain consistent with the data taken from HQAF, "30-Year Aviation Procurement Report." Where the analysis deviates from this approach and eliminates LAAR and/or LiMA from consideration, a note will be made of it.

Other, more detailed characterizations of attribute diversity are possible, of course. Within the category of global intelligence, surveillance, and reconnaissance (ISR), for example, a relevant attribute might consider whether systems are manned (e.g., MC-12, RC-135, etc.) or unmanned (MQ-1, MQ-9, RQ-4, etc.). Another collection of attributes might include the types of intelligence collected by these various ISR platforms: geospatial intelligence (GEOINT) and imagery intelligence (IMINT); signals intelligence (SIGINT), including communications intelligence (COMINT), electronic intelligence (ELINT), and foreign instrumentation signals intelligence (FISINT); and measures and signals intelligence (MASINT).[15]

Just as we can consider a force structure in terms of attribute-based measures of diversity, we can apply the distance and entropy techniques described in chapter 2 to measuring diversity across type as it relates to force structure. For example, consider one small segment of the Air Force inventory—the fighter/attack category comprised of A-10, F-15C/D, F-15E, F-16C/D, F-22, F-35A, and LAAR aircraft.[16] Figure 7 describes a notional taxonomy of ideal aircraft types on the basis of a series of binary categories.[17] The heavy black lines indicate binary paths to the seven ideal types found in the Air Force inventory, while the light gray lines indicate paths to degenerate aircraft types not found among the Air Force inventory of fighter/attack platforms.[18]

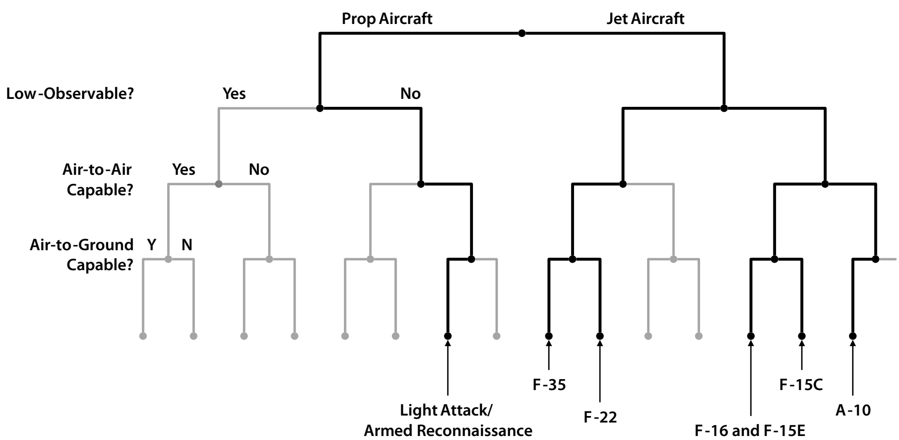


Figure 7. Notional fighter/attack aircraft taxonomy

Such a taxonomy makes it possible to describe Weitzman and Hamming distances among the various platforms (table 3).[19] Note that in terms of the ideal-type categories presented in the taxonomy in figure 7, the F-15E and F-16C/D platforms are functionally equivalent.[20] Table 3's metrics also show this equivalence: the

distance calculations for the two platform types are identical, and the distance between the two ideal types is zero.

Table 3. Notional Weitzman/Hamming distances among fighter/attack platforms

	A-10	F-15C/D	F-15E	F-16C/D	F-22	F-35A
F-15C/D	2/2					
F-15E	2/1	1/1				
F-16C/D	2/1	1/1	0/0			
F-22	3/3	3/1	3/2	3/2		
F-35A	3/2	3/2	3/1	3/1	1/1	
LAAR	4/1	4/3	4/2	4/2	4/4	4/3

Using the taxonomy in figure 7 and the calculations in table 3, we can (as chapter 2 indicates) calculate at least two measures of diversity in the fighter/attack force structure of the Air Force: Weitzman diversity and the effective number of types. Table 4 summarizes these measures. For each diversity measure, four values are reported. Each was calculated using both the Weitzman and Hamming distances shown in table 3, and each computation was repeated for force structures that both include and exclude the LAAR program. Notice that the removal of the LAAR from the force structure has a noticeable impact on both diversity measures (i.e., the measures are sensitive to force-structure changes, as one would expect and require of such a metric).[21]

Table 4. Diversity measures for the projected 2012 Air Force

	Weitzman diversity		Effective number of types	
Distance type	**Weitzman**	**Hamming**	**Weitzman**	**Hamming**
With LAAR	11	5	4.2	3.1
Without LAAR	7	4	3.3	2.6

The final diversity measure proposed in chapter 2 to characterize diversity across types involves simply calculating the entropy of the system or answering the question, How many types are there and how evenly is the total number of platforms spread across those types? Considering only the fighter/attack platforms discussed above, the Shannon and Simpson entropies for the projected 2012 force structure are 1.42 and 0.70, respectively.[22]

The foregoing discussion of diversity in connection with the Air Force's projected 2012 aircraft inventory demonstrates with multiple measures the self-evident proposition that this force structure is, in fact, diverse. Thus, the first descriptive characteristic associated with the classification of this force

structure as a complex adaptive system is satisfied. The question of the influence exerted by this diversity, the consequences associated with diminishing diversity through elimination of types (e.g., LAAR), and the direction this indicates for the analysis of force structures remains an open question and is addressed in chapter 5.

Interdependence

Recall from chapter 2 that the elements of a complex adaptive system are said to be interdependent in the sense that the fitness of the elements is mutually defined. Innumerable examples of interdependence are readily observable in force structures, but three in particular should illuminate the complexities of the issue. These focus on how elements within a force structure are interrelated (cost and capability) and how, on another scale, discrete force structures interact with one another.[23]

The interdependencies of force-structure elements as a function of cost in a fiscally constrained environment are obvious. Given a fixed budget and a fixed set of available platforms and capabilities, a desire to acquire more of a given platform or capability must come at the expense of some other platform(s).[24] The same effect is induced by a diminishing budget. The Department of Defense (DOD) fiscal year 2013 budget proposal, for example, suggests reducing the base budget by $259 billion over five years.[25] To accomplish this, reductions were adopted in the wider DOD force structure. Some specific manifestations in the material force structure of the Air Force include an increased budget allocation for a new aerial refueling tanker, delays and restructuring in the Joint Strike Fighter (F-35) program, and termination of the RQ-4 Global Hawk (Block 30) and C-27A aircraft programs.[26] Every element of force structure is intrinsically dependent on every other element on the basis of their mutual effects on each other via the medium of a finite budget.

Elements of the Air Force's force structure are also interdependent in the sense that their capabilities may be complementary and mutually enabling. Consider, for example, the capability relationships described in figure 8. Each of the platforms listed is capable of performing some mission in the absence of the other three types.[27] For example, the air-superiority platform can take off, land, and engage air targets without the benefit of a strike platform, aerial refueling, or C2 assistance. It is constrained in doing so, however, by its fuel capacity and its onboard sensors. Adding an aerial-refueling capacity extends the range and increases the efficiency of those air-superiority platforms, and adding a C2 platform increases their efficiency in finding and engaging enemy targets. Similarly, the presence of air-superiority platforms enables the air

environment so that relatively vulnerable systems such as the E-3 AWACS and KC-135 can operate more safely. As with increased operational range for air-superiority platforms, B-2 strike missions (e.g., nonstop flights from Whiteman AFB, Missouri, to employ precision-guided munitions on the first night of Operation Enduring Freedom) would not be possible without aerial refueling.[28] At the same time, while air-superiority platforms are able to suppress an adversary's capability to interdict strike platforms air to air, those same strike platforms—by striking at an adversary's ground-based air defenses and air bases—can enable the air environment for air-superiority platforms.

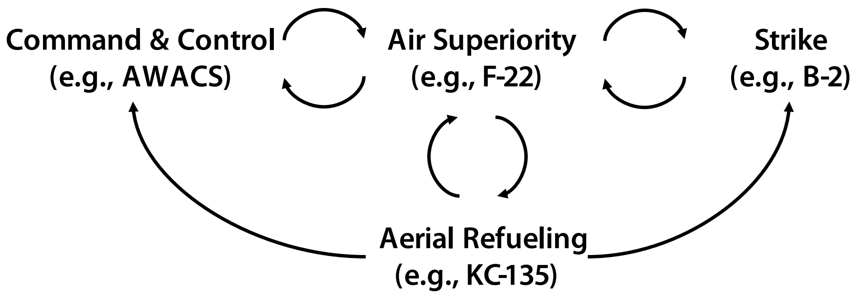


Figure 8. Simple capability relations in Air Force platforms. A relational diagram like that shown here is a naïve representation of the dynamical system of force structure. The interactions shown are all positively correlated (an increase/decrease in one variable induces an increase/decrease in the related variable). A technical introduction to the theory of system dynamics can be found in Katsuhiko Ogata, *System Dynamics*, 4th ed. (Upper Saddle River, NJ: Prentice Hall, 2003).

Nonlinear relationships emerge quickly from the interdependencies described in figure 8. If the effectiveness of the AWACS depends on the availability of the KC-135, the effectiveness of the KC-135 depends on an environment created by the F-22, and the effectiveness of the F-22 depends on the presence of the AWACS, a self-referential dependency exists. This represents a systemic nonlinear dependency, and as these self-referential dependencies interact, nonlinearities are compounded.

At another scale, interdependencies exist between discrete force structures, like those of the United States and the People's Republic of China (PRC) or Iran. According to the National Air and Space Intelligence Center, for example, the PRC is "acquiring new conventionally armed medium-range ballistic missiles to conduct precision strikes at longer ranges. These systems are likely intended to hold at risk, or strike, logistics nodes and regional military bases including airfields and ports."[29] The theoretical effectiveness of the US Air

Force operating in the western Pacific is dependent on the efficacy of the PRC in denying access to airfields. Of course, the efficacy of mentioned medium-range ballistic missiles in denying access to airfields is also a function of the ability of the force structure of the US Air Force to interdict those missiles. Thus, the two force structures are interdependent.[30]

Adaptation

Adaptation in the tools of military force is not a new phenomenon.[31] New technologies and new applications of old technologies have always been used to seek advantage in conflict. Comparing the present and past, classical scholar Victor Davis Hanson writes,

> Since the advent of gunpowder, moderns have tended to deprecate the idea of body armor. The fiery offensive arts have for some six centuries overshadowed the much older sway of personal defense, so much so that surviving panoplies in modern museums seem ridiculous to the modern eye. Nevertheless, the age-old tension between attack and defense is not static. Only recently an emphasis on body armor has returned as scientists have at last discovered combinations of synthetic fibers, plastics, ceramics, and metals that can withstand even the onslaught of high-velocity, metal-alloy bullets and shrapnel fragments, which can strike the body instantaneously with incredible force and numbers. Ironically, the catalyst for Kevlar helmets, bulletproof vests, and assorted insertable ceramic plates are somewhat similar to those that led to heavily armored hoplites: first, such protection can save lives; second, the value of each combatant is now prized in a way not true of previous wars of the twentieth century.[32]

It should thus come as no surprise that force structures adapt to changing technologies and circumstances. In fact, to see adaptation operating in the force structure of the United States Air Force, one need only note the progression in pursuit/fighter aviation from the P-51 to the F-22 (with aircraft as various as the F-86, F-105, F-4, and F-15 in between) or the evolution of bomber aviation from the B-17 to the B-2 (with the B-29, B-36, B-52, and B-1 in between). Nevertheless, a slightly more detailed discussion is illuminating.

The events of World War II offer a number of examples of force-structure innovation. Faced with extraordinary attrition during bombing raids against industrial targets in Schweinfurt, Germany, the Army Air Force was able to exploit available technologies and a wartime industrial base to rapidly field long-range escort versions of the P-51. Absent such an adaptation in the force structure, the air war in Europe would have been a very different conflict for the United States.[33] Another adaptive dynamic played out in the Pacific theater of World War II. Historian Mark Peattie describes the early successes of Japanese naval aviation: "In the first chaotic months of the war, the fighter pilots of the Japanese navy flew and fought in unchallenged triumph in advance of the near unchecked progress of their nation's ships and men."[34] In addition to

the adaptations of tactics employed by US pilots in countering the initial advantages enjoyed by the Japanese, material adaptations occurred as well. Most powerfully, perhaps, the Japanese industrial base was not able to respond effectively to the US entry into the war. As Richard Overy relates, "The number of fighters produced was simply not adequate for that task of regaining air superiority. That the number of aircraft produced was insufficient was demonstrated by the wide difference in strength between the Japanese and American air forces in the later stages of the war." This difference in the capacity of each side to adapt to the quantitative demands placed on their respective force structures "was made worse for the Japanese forces because of the relative decline in performance. Against the new Allied aircraft, even the Zero fighter was considerably inferior and other Japanese aircraft completely outmoded."[35] Quantitative and qualitative adaptations were both critical to US air power successes in World War II.

As previously mentioned, adaptation and interdependence together constitute necessary and sufficient conditions for the creation of coevolutionary systems. In each of the examples given here, the influences to which the elements adapted were treated as exogenous variables. Interdependence brings those elements inside the conceptual models and requires that they be considered together. These situations involving adaptation to endogenous influences are addressed in the context of coevolution.

Nonlinearity

The fact that force structures exhibit the characteristics of nonlinear (though not necessarily chaotic) systems as a direct consequence of interdependencies among system elements has been noted. As such, the fundamentally nonlinear character of force structure has already been established. Nevertheless, it is worth exploring a simple manifestation of the nonlinearities induced by interdependency and their influence on the analytical problem of determining capabilities and associated quantities for the Air Force to meet its national security obligations.

Suppose the Air Force has exactly two aircraft platforms from which to choose—one optimized for air superiority missions and the other for strike missions (e.g., the F-22 Raptor and F-35A Lighting II).[36] While obviously a gross oversimplification of the Air Force's portfolio of available platforms and capabilities, this scenario is sufficient to highlight the influence of nonlinear interdependencies. The force-structure decision the Air Force faces is then how many of each platform to procure in the face of operational requirements and fiscal constraints.

One approach to making such a decision is to assess the performance of various (or all possible) force structures in some scenario and to choose a force structure based on some optimality condition (e.g., least cost).[37] In its simplest form, such a scenario requires a characterization of the work required by the force structure (e.g., the number of targets to destroy) and a description of the constraints within which the force structure must operate (e.g., basing constraints, enemy order of battle, etc.). Rear Adm J. C. Wylie observes in his classic work *Military Strategy: A General Theory of Power and Control* that statistical approaches like the one described here have been particularly useful with respect to the analysis of cost effectiveness and force structure for an airpower since "the air theory is predicated on delivery of destruction" and "destruction is a finite and measureable phenomenon."[38] What follows is a mathematical formulation of such a scenario and a cost-effectiveness calculation.

To describe an elementary probabilistic model for the behavior of a force structure comprised of some mix of air-dominance and strike-optimized platforms in prosecuting a collection of adversary targets, characterizing the probability that a given aircraft will achieve the desired effect against a given target is necessary.[39] This probability requires both that the attacking aircraft reach the target (call this event R) and, given that the target is reached, successfully engage it (call this event K). Symbolically, this is expressed as

$$P_{Kill} = P(R \cap K) = P(K|R)P(R).$$

The first probability is simply the lethality of the attacking aircraft against the given target.[40] The second, the probability of reaching the target, is more complex since the attacking aircraft can reach the target in one of two ways. Either the target is undefended (call this event U) or the target is defended, and the attacker reaches it in spite of these defenses (call this event D). These two events are a collectively exhaustive and mutually exclusive description of R, resulting in the expression

$$P(R) = P[(U \cap R) \cup (D \cap R)] = P(U) + P(D \cap R).$$

Each of the terms in the right-hand side of this equation can be parsed into simpler component probabilities. Let the events A and G represent that the target is defended by air- and ground-based assets, respectively. Further, assume these events are independent of one another.[41] This allows the probability that the target is undefended to be described in terms of its complement

$$P(U) = 1 - P[(A \cap \bar{G}) \cup (\bar{A} \cap G) \cup (A \cap G)] = 1 - P(A) - P(G) + P(A)P(G).$$

Similarly, the probability that the target is defended and reached by the attacking aircraft can be written as

$$P(D \cap R) = P(R \cap A \cap \bar{G}) + P(R \cap \bar{A} \cap G) + P(R \cap A \cap G).$$

Each of the terms in this expression can be further decomposed using the properties of conditional probability and the assumption of the independence of events A and G. This yields the expression

$$P(D \cap R) = \rho P(A)[1-P(G)] + \tau[1-P(A)]P(G) + \tau\rho P(A)P(G),$$

where the parameters ρ and τ describe the survivability of the attacking aircraft in the face of air-based and ground-based defenses, respectively.[42]

Each of the expressions for $P(U)$ and $P(D \cap R)$ is now articulated in terms of the component likelihoods that the given target will be defended by either air- or ground-based systems. The next step is to develop an expression for each of these probabilities, $P(A)$ and $P(G)$. Each will be expressed in terms of the event that the defender intends to shield the target with those assets: I_A and I_G, respectively. Using this notation and the principles of conditional probability, $P(A)$ and $P(G)$ become

$$P(A) = P(A|I_A)\mathrm{P}(I_\mathrm{A})$$

and

$$P(G) = P(G|I_\mathrm{G})P(I_G).$$

Given the already stated assumption that every target is essentially equivalent, the simplest approach to defining the quantities $P(I_A)$ and $P(I_G)$ is to consider them as simple densities or ratios of the relevant number of defensive assets to the number of targets to be defended.[43]

Now, it remains only to unravel the probabilities $P(A|I_A)$ and $P(G|I_G)$. These expressions pose the question, what is the probability that the target remains defended given the intent of the defender? In other words, what is the probability that the defensive assets placed around the target have not been interdicted by some other attacking aircraft in the scenario? To answer this question, write $P(A|I_A)$ as

$$P(A|I_A) = P(\overline{K}_1 \cap \overline{K}_2) = P(\overline{K}_1|\overline{K}_2)P(\overline{K}_2),$$

where K_1 and K_2 represent the events that the air-based defender is interdicted by an air-dominance or strike aircraft, respectively. The event that the defender is not interdicted by an air-dominance platform, $\overline{K}_1$, can happen in either of two ways. First, it is possible the air-based defender is never engaged by an attacking air-dominance platform (other than the aircraft seeking to

strike the ground target defended by that air-based defender); express this as $\overline{E}_1^A$. Alternatively, it is possible that the defender was engaged by an attacking air-dominance platform, an event written as E_1^A, and the defender survived the engagement, an event characterized in terms of the lethality of the attacking platform against the defender. Similarly deconstructing the event $\overline{K}_2$(and simplifying the resulting expression substantially) yields the relation

$$P(\overline{K}_1|\overline{K}_2)P(\overline{K}_2) = [1-\alpha_1 P(E_1^A)] \cdot [1-\alpha_2 P(E_2^A)],$$

where α_1 and α_2 represent the lethality of the attacker's air dominance and strike platforms against the defender's air-based assets.[44] Similarly,

$$P(G|I_G) = [1-\gamma_1 P(E_1^G)] \cdot [1-\gamma_2 P(E_2^G)],$$

where γ_1 and γ_2 represent the lethality of the attacker's air-dominance and strike platforms against ground-based defenders, respectively.

It is in the engagement probabilities described above that the inherent nonlinearity of the system becomes evident. If (and only if) these probabilities are taken as constant with respect to the decision variables in the model (the number of air-dominance and strike platforms), the system described reduces to a linear system.[45] This assumption is intuitively problematic, though. For example, if one assumes the probability that an air-based defender is engaged by an air-dominance platform that is independent of the number of air-dominance platforms, then the probability that an air-dominance platform has interdicted the defender is the same for force structures with one, 10, or even 100 air-dominance platforms. Clearly, the assumption of linearity in this system is a difficult one to justify. Is the assumption salient, though? That is, does the assumption bear heavily on the understanding of the system modeled and the utility of the force mixes derived from it?

An instantiation of this simple probability-based model describing the interactions between two types of attacking platforms and an adversary force structure makes the answer to this question clear. As indicated above, the probability model requires a number of inputs describing the performance of the various platforms (lethality and survivability in each of the air-to-air and air-to-surface roles).[46] Notional performance parameters for this model are shown in table 5. Note that each platform has a capability in both air-to-air and air-to-ground missions, but each is three times more effective than the other in its intended role.

In addition to these performance parameters, we need to define the scenario against which the force structure will be assessed. As mentioned, this entails portraying the adversary order of battle (the number of air- and ground-based defenders and strategic strike targets). For this example, assume these

values are all equal to 150.[47] Finally, assume that the number of friendly aircraft permitted in the scenario is constrained (e.g., by basing limitations) and cannot exceed 650.

Table 5. Notional aircraft performance parameters

Performance parameter		Platform type	
		Air dominance	Strike
Air-to-air	Lethality (α)	0.75	0.25
	Survivability (ρ)	0.75	0.25
Air-to-surface	Lethality (γ)	0.25	0.75
	Survivability (τ)	0.25	0.75

These values completely describe the sample scenario, but to illustrate the salience of assumptions of linearity requires a characterization of the engagement probabilities $P(E_i^A)$ and $P(E_i^G)$ for $i = 1, 2$. As noted, one option is to assume these probabilities are constant, rendering the probability model linear. For this example, set these probabilities so that for $P(E_i^A) = P(E_i^G) = 0.9$ for $i = 1, 2$. The results associated with an assumption of linearity are shown in figure 9. Each point in the coordinate plane shown in the diagram represents a force mix of air-dominance and strike platforms. The red line marks the boundary between those force mixes able to attrite the adversary target set despite the defenses arrayed against them (above the line) and those unable to do so (below the line). The blue line illustrates the basing constraint. Force mixes above this line are too large and therefore inadmissible, while force mixes below the line are permitted. These curves define the so-called feasible region for the force mixes, shown as a shaded triangle. Any force structure in this region meets the conditions described.[48]

Compare figures 9 and 10. To create figure 10, a number of requirements were placed on the engagement probabilities based on an intuition regarding the appropriate characteristics for such a probability. First, the engagement probability should be a monotonically increasing function of the number of attacking aircraft; the more air-dominance platforms in the scenario, the more likely they are to interdict a defensive system. Second, for each aircraft type, the engagement probability should be a monotonically decreasing function of the number of the other type; with more strike aircraft in the scenario, an air-dominance platform is less likely to interdict a defensive system. Third, the engagement probabilities should reflect the relative performance characteristics of the various aircraft; air-dominance platforms are more likely to interact with air-based defensive systems and strike platforms with ground-based defensive systems. Finally, engagement probabilities should increase

slowly for very small and very large numbers of a given platform. This precept reflects the notion of increasing returns at the low end of the force structure and of diminishing returns at the high end (fig. 10).[49]

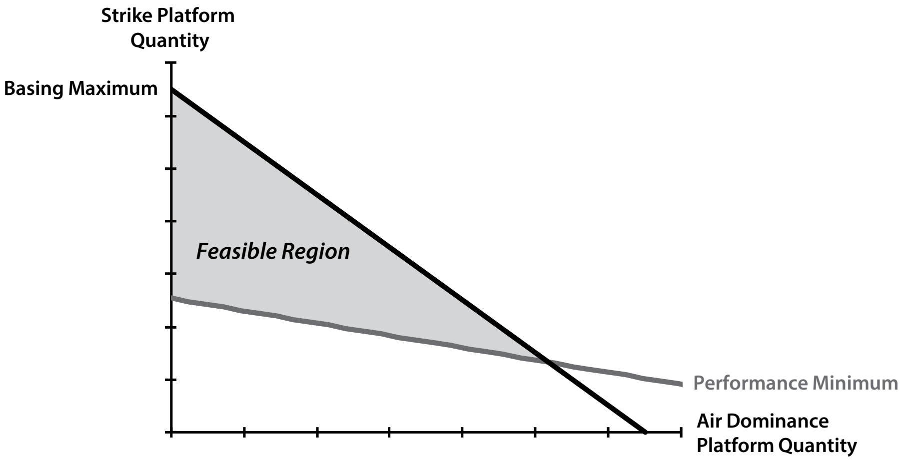


Figure 9. Linear probability model results. (*Adapted from* Eric M. Murphy and Michael D. Payne, "Foundations of Force Structure Analysis: A Preliminary Investigation of Methodological Choices and Consequences" [lecture, Military Operations Research Society Symposium, United States Coast Guard Academy, New London, CT, May 2008]).

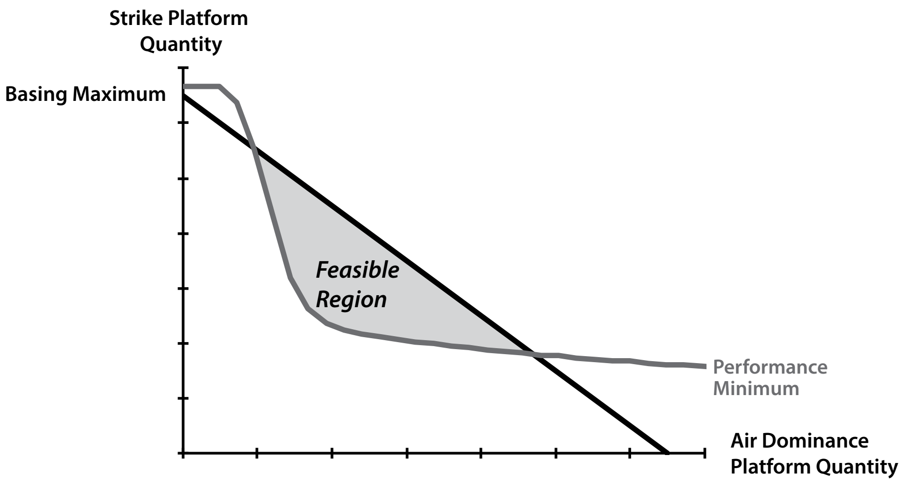


Figure 10. Nonlinear probability model results. (Adapted from Eric M. Murphy and Michael D. Payne, "Foundations of Force Structure Analysis: A Preliminary Investigation of Methodological Choices and Consequences" [lecture, Military Operations Research Society Symposium, United States Coast Guard Academy, New London, CT, May 2008]).

Two conclusions are clear. First, as already discussed, blanket assumptions of linearity in the behavior of force structure are almost certainly inappropriate; force structures are nonlinear systems. Second—even in this simplest of examples—inherent nonlinearities profoundly impact the behavior of force structure and the lessons to be taken from analysis of these behaviors (e.g., conclusions regarding the number and types of aircraft to procure).

Emergence

Recall Herbert Simon's intuitive characterization of emergence. He states that in complex systems "the whole is more than the sum of the parts, not in an ultimate, metaphysical sense, but in the important pragmatic sense that, given the properties of the parts and the laws of their interaction, it is not a trivial matter to infer the properties of the whole."[50] These properties of the whole (macro phenomena)—as opposed to properties of individual elements within the whole (micro phenomena)—are considered emergent. Examples of such properties are not difficult to find in force structure.

In the above description of nonlinearities fundamental to the behavior and performance of force structure, for instance, the phenomena of increasing returns from additional platforms in small force structures and decreasing returns for large force structures are weakly emergent phenomenon.[51] In the above example, the force structure elements are air-dominance and strike platforms, and the mission is described in terms of traditional kinetic military activity. Similar emergent phenomena are present in other types of platforms and military missions. Consider the problem of airborne early warning in supporting the mission of homeland air and cruise-missile defense. It has been shown that in this mission, the capability of a surveillance force structure depends critically and nonlinearly on the number of platforms in the force structure in a manner not dissimilar to that developed describing the engagement probabilities above.[52]

Another example of emergent characteristics and behavior in force structure looks ahead to the potential for swarms of autonomous and semiautonomous unmanned aerial systems.[53] The *United Stated Air Force Unmanned Aircraft Systems [UAS] Flight Plan* offers a vision for autonomous action by collections or swarms of systems:

> The near-term concept of swarming consists of a group of partially autonomous UAS operating in support of both manned and unmanned units in a battlefield while being monitored by a single operator. Swarm technology will allow the commander to use a virtual world to monitor the UAS both individually and as a group. A wireless ad-hoc network will connect the UAS to each other and the swarm commander. The UAS within the swarm will fly autonomously to an area of interest (e.g., coordinates, targets,

> etc.) while also avoiding collisions with other UAS in the swarm. These UAS will automatically process imagery requests from low level users and will "detect" threats and targets through the use of artificial intelligence (AI), sensory information and image processing. Swarming will enable the UAS network to deconflict and assign the best UAS to each request.[54]

In a sense, every behavior of such an aggregate system is emergent. The interaction of individual system elements at the micro level produces behavior and aggregate decision making at the macro level from the bottom up.[55] The particular emergent behaviors in such a system will vary depending on the character of the interactions among the system components, and the aggregate behavior is more difficult to describe a priori than previously discussed emergent phenomena.[56] Some of those behaviors might include flocking, obstacle avoidance, and robustness (since removal of individual elements will induce adaptive actions in the remaining elements to accommodate altered conditions).[57]

Another example of an emergent phenomenon in the realm of force structure is seen in the contentious debate over the relative merits of quantity and quality in the procurement of weapons systems. As the Cold War ended, economist William Rogerson observed, "Many institutional analyses of defense procurement raise the issue that the military's choice along the quality-quantity frontier for various weapons systems seems to be biased toward 'too high' a level of quality. That is, it is argued that the same expenditures would produce a more effective defense if larger numbers of less elaborate and less technically sophisticated (and therefore cheaper) weapons were purchased." According to Rogerson, traditional explanations for this bias toward quality over quantity are rooted in the competitive economic incentives underlying the design and acquisition of military systems; that is, military decision makers, engineers, and defense contractors derive private value from increased quality not available in procurement strategies with a preference for quantity.[58] Rogerson goes on to develop an alternative explanation for the apparent bias toward quality in procurement based on institutional organization. He builds a mathematical case that the observed phenomenon arises not from the local, self-maximizing economic behavior of the individual actors but from the organization of those actors.[59] In either case, of course, emergence is an observable characteristic of force structure.

Coevolution

As stated in this chapter's introduction, the system characteristics of interdependence and adaptability are necessary and sufficient conditions for a sys-

tem to exhibit coevolutionary behavior. Since force structures exhibit these characteristics, they must necessarily also exhibit coevolutionary behavior. A few observations and examples of coevolution in action are illuminating, however.

One of the defining principles underlying the interactive dynamics of US and other military force structures (both state and nonstate) is the generally overwhelming capability advantage the United States enjoys in strictly conventional terms. As Arthur Cebrowski expresses, this advantage has led potential adversaries "to compensate for US conventional military superiority by developing asymmetric approaches and capabilities. Terrorists attacked non-combatants; other adversaries used low-end indiscriminate weapons such as mines . . . [and] adversaries such as Iran and North Korea are investing heavily in WMD [weapons of mass destruction] and a wide range of delivery methods in hopes of deterring or frustrating the deployment and employment of highly lethal US combat capabilities."[60] In other words, "the rise of asymmetrical warfare is largely our own creation" in the sense that the United States created the conditions incentivizing the approach to force structure and warfare exploited by potential adversaries.[61]

The US military, of course, responds to these attempts at creating asymmetric advantage with adaptations of its own. Part of the response to irregular tactics in Iraq and Afghanistan, for example, has been to place a premium on remotely piloted aircraft (RPA) to support those conflicts. As part of its deliberations on the 2010 National Defense Authorization Act, for example, the Senate Armed Services Committee affirmed that "the Air Force is required to acquire and maintain enough Predator and Reaper unmanned aerial vehicles (UAV), along with the processing, exploitation, and dissemination (PED) capacity for 50 combat air patrols (CAP)."[62] State and nonstate actors have responded to this transformation of the force structure of the Air Force as well. Insurgents in Iraq, for example, were able to exploit the intelligence provided via nonsecure, line-of-sight communications for an extended period in 2008 and 2009 with negative effects on US operations.[63] More recently, claims have emerged that Iranian engineers were able to exploit vulnerabilities in the control of an RQ-170 Sentinel RPA and cause that aircraft to land in Iran.[64] This action-reaction dynamic will continue as the United States makes changes to prevent future occurrences of this type and adversaries respond to those measures in turn.

This same phenomenon plays out at a level more closely related to the tactical and operational levels of war and the direct employment of force structure. For example, the lens of complexity theory has been applied to understand the contest for control of the air. Maj Skip Pribyl, a US Air Force fighter pilot, suggests,

> As air attack and air defense systems contest airspace for freedom to attack and freedom from attack, they likewise co-evolve. In the fast-paced arena of air combat, strike packages penetrate air defense screens, and pilots constantly make decisions based on the unfolding situation. Elements maneuver to kill enemy fighters, react to enemy missiles, and flow the strike package toward its targets. What were once orderly formations in the marshalling area quickly descend into a swarming melee. Local elements must adapt to changing threats from enemy reactions and the tactical environment. Their decisions, in turn, drive the enemy to new courses of action. While the strike package may get to the target, the next time these opponents meet, they will have each learned from previous engagements. Subsequent battles will look different, and next time the defenders may win.[65]

While Pribyl's work and the description given here generally concentrate on the tactical and operational employment of force structure by learning entities and organizations, the coevolution of force structure itself is not ignored. He claims that "thinking about co-evolution in air warfare has practical relevance to today's armed forces. In the ongoing struggle to control the air, stealth platforms and information superiority have enabled US-led strike packages to neutralize air defenses for the past fifteen years, but history suggests any niche advantage will not hold. Indeed, air defenses have responded by proliferating advanced counter-technologies, and each new war brings new challenges demanding adaptation."[66]

This sentiment is echoed by Scott Stephenson, a professor at the US Army's Command and General Staff College, in the context of revolutions in military affairs (RMA). Following Williamson Murray and MacGregor Knox, Stephenson defines an *RMA* as a phenomenon requiring "the assembly of a complex mix of tactical, organizational, doctrinal, and technological innovations in order to implement a new conceptual approach to warfare or a specialized sub-branch of warfare." These evolutionary earthquakes in military affairs have important and enduring properties rooted in their coevolutionary nature. As Stephenson notes, "Those that live by the RMA may well die by the RMA, and in time, the competition will catch up" since "dominance in an area of warfare will inspire others to launch their own RMA" and "even before it matures on the battlefield, an RMA may generate a 'counter-RMA.' "[67] As the militaries seek advantage through evolving technologies, doctrine, and organization, they cocreate the dynamic or dancing fitness landscape in which they interact. Thus, mutual adaptation and coevolution occur at the level of employment of a given force structure and in the creation of new force structures over time within and between militaries.

Path Dependence

Perhaps the most salient and clearest example of path dependence as a consequence of positive feedback in force structure is found in the area of stealth or low-observable (LO) technologies. In the early days of Air Force LO technologies, Jasper Welch identified factors associated with the fielding of stealthy aircraft and the potential responses to this fielding by an adversary. Two of these warrant discussion here.

First, Welch states, "In the case of stealthy aircraft, the straightforward countermeasure is improved radar. Indeed, if the degree of stealth is modest enough, then even upgrades of existing radars might well suffice to return matters to the status quo ante."[68] This establishes a mutually reinforcing feedback relationship between the stealthy aircraft and the radar-based air defenses. Improved stealth encourages advances in defensive systems that, in turn, incentivize further enhancements in and reliance on stealth.

Second, Welch observes that "the requirements of stealth on an aircraft's design can be conceptually considered as an additional constraint on the design." One of the impacts Welch describes is an increase in the per-unit cost of stealth aircraft in comparison to similar nonstealthy aircraft. He argues convincingly via a scenario-based example that these direct costs are more than offset in terms of effectiveness: "In the areas of penetration, target acquisition, and target vulnerability, large indirect effectiveness increases accrue to the stealthy aircraft; and large indirect cost increases accrue to the non-stealthy aircraft."[69] The purpose of this discussion is not to compare the relative merits of stealthy and nonstealthy aircraft, of course; rather, Welch's argument illuminates another set of positive feedbacks incentivizing a migration toward an LO force structure. Increased cost and performance both offer incentives toward smaller force structures. These smaller force structures, however, incentivize further improvements in stealth (and other capability areas) since the smaller force structure results in greater marginal impacts from the loss of individual aircraft in combat.[70]

So (at least) two positive feedback mechanisms are operative in the case of force structures comprised of stealthy aircraft. As Brian Arthur would characterize it, the predicted result of such positive feedbacks is that the force structure in question becomes locked into a path dependent on LO technologies.[71] This is, in fact, the situation in which the Air Force finds itself, as stated by a former Air Force chief scientist:

> Low-observable technologies and the systems that employ them for long-range penetrating and persistent strike are among the most distinguishing elements of the Air Force. While advanced IADS [integrated air defense systems] may over time create an

> increasingly challenged environment for these critical systems, low-observable systems will remain essential for the ability they give to penetrate defended airspace, for the sensitivities they demand in the air-defense systems of potential adversaries, and for the potential secondary benefits they can create for other technology-based capabilities. Technologies to extend affordable LO capabilities will remain essential.[72]

That the Air Force is reliant upon LO technologies and is likely to remain so for the foreseeable future is not necessarily to be regretted. This state may, in fact, be optimal for the Air Force and for the United States. Rather, this discussion is merely intended to illustrate the agency of path dependencies in the evolution of force structures for the US Air Force, and no illustration of path dependence acting on force structure could be clearer than this.

Notes

1. Joint Publication 1-02, *Department of Defense Dictionary*, 226–27.
2. DOD, "QDR 101: What You Should Know."
3. For example, the report establishes a guideline that the Air Force will comprise eight intelligence, surveillance, and reconnaissance (ISR) wing equivalents with approximately 380 primary mission aircraft, 30 to 32 airlift and aerial refueling wing equivalents with 33 primary mission aircraft per wing equivalent, etc. DOD, *Quadrennial Defense Review Report*, 1 February 2010, 45–47.
4. The 12 USAF core functions are nuclear deterrence operations, global precision attack, air superiority, rapid global mobility, global integrated ISR, command and control, special operations, personnel recovery, building partnerships, agile combat support, space superiority, and cyberspace superiority. For their descriptions, see Air Force Doctrine Document (AFDD) 1, *Air Force Basic Doctrine*, 43–53.
5. Though not discussed in this paper, this approach is universal with respect to force structure. That is, it is applicable to the force structures of other services, the DOD as a whole, and to the military force structures of other nations.
6. *Merriam-Webster's Collegiate Dictionary*, 11th ed., s.v. "heuristic."
7. Jomini, *Art of War*, 63–64.
8. The following discussion excludes consideration of diversity within types (variation).
9. AFDD 1, *Air Force Basic Doctrine*, 43–53.
10. The list of platforms and their association with the Air Force core functions are based on projected total active inventory for 2012 and derived from Headquarters USAF, "Air Force 30-Year Aviation Procurement Report." These data are the source for all diversity measures in this section.
11. That is, each aircraft type corresponds to exactly one core function.
12. USAF, "F-16 Fighting Falcon"; and USAF, "F-15E Strike Eagle." The F-16 was, in fact, conceived as an air superiority platform. For a narrative describing the F-16's genesis and development, see Coram, *Boyd*, 232–313.
13. The B-52, for example, has deployed as a platform providing global precision strike capabilities in the Vietnam War (1965–1973), Operation Desert Storm (1991), Operation Allied Force (1999), Operation Enduring Freedom (2001), and Operation Iraqi Freedom (2003). A similar story holds for the B-2. See Thompson, "Operations over North Vietnam, 1965–1973,"

107–26; Olsen, "Operation Desert Storm, 1991," 177–200; Mason, "Operation Allied Force, 1999," 225–52; Lambeth, "Operation Enduring Freedom, 2001," 255–77; and Murray, "Operation Iraqi Freedom, 2003," 279–96.

14. USAF, "E-3 Sentry (AWACS)"; and USAF, "E-8C Joint STARS."

15. AFDD 2-0, *Global Integrated Intelligence, Surveillance, and Reconnaissance Operations*, 38–40.

16. As previously noted, the Air Force has cancelled the LAAR program. It is included here for two reasons: (1) it remains in the projected force structure data supplied by HQ USAF for this analysis, and (2) it provides a contrast with the remaining ideal types in the taxonomy and associated distance calculations. Multiple diversity measures will be computed to illustrate the effects of its inclusion/exclusion.

17. The branches of such a tree don't have to be binary. This form was selected for convenience in generating ideal types and to conveniently accommodate the distance metrics used later.

18. While this diagram shows only those aircraft falling into the general category of fighter/attack platforms, the approach used here could be extended to include other types or categories of aircraft. Consider the rightmost degenerate type, for example. This ideal type comprises those aircraft that are jet propelled, nonstealthy, and lack air-to-air and air-to-ground armaments. This describes entire categories of aircraft shown in table 2, including rapid global mobility (e.g., C-17, C-21, KC-135, KC-10, etc.), global integrated ISR (MC-12, MQ-1, RQ-4, etc.), and C2 platforms (e.g., E-3 AWACS, E-8 JSTARS, etc.). Adding further branch questions could expand the diagram to include these and other aircraft types.

19. For descriptions of computational methods for these measures, see Page, *Diversity and Complexity*, 72–73; and Hamming, "Error Detecting and Error Correcting Codes," 147–60. Note that the Weitzman distance and diversity depend critically on the order in which the binary branches appear. For taxonomic trees in ecology, this sequence is well defined on the basis of the time lines on which species diverge from common ancestors. In the example given, however, the order is more arguable. Another interesting possibility for the construction of taxonomies like that shown here is based on principles for describing technological systems. Brian Arthur discusses this concept—using the F-35 Lightning as an example—in *Nature of Technology*, 39–42.

20. Functional differences among these platforms are of course obvious (number of engines, crew size, combat radius, radar signature, etc.). This example is intended to be illustrative rather than exhaustive.

21. One of the advantages Page notes for Weitzman diversity is its sensitivity to species loss. Page, *Diversity and Complexity*, 73.

22. These computations exclude the LAAR program. For reference, if the given number of total platforms were spread evenly across the platform types, maximizing entropy, then these values would be 10.75 and 0.83. The lower observed values reported in the table are a function of the disproportionately large number of certain platforms (especially F-16s) in the 2012 force structure and the comparatively very small numbers of other platforms (especially F-22s and F-35s).

23. Some analysts will use the terms *scope* and *scale* to indicate distinct properties in analysis. Scale, for example, refers to the unit of analysis (e.g., the leaves on a tree are examined rather than the tree) while scope refers to the breadth of the analysis (e.g., a single leaf, all the leaves on a tree, all the leaves in a forest). Dolman, *Pure Strategy*, 159–61. While the nuanced difference between these two concepts can add value, a change in scope is, in many ways, inextricable from

a change in scale (e.g., when considering all the leaves in the forest, the unit of analysis has implicitly shifted to forests rather than leaves). In this analysis, *scale* is used interchangeably with *scope* unless a distinction is contextually necessary.

24. This is a ceteris paribus outcome. From a planning perspective, it may not always be the case that platforms/capabilities are available in fixed increments. That is, if capabilities are separable and transferable, it may be possible to acquire a radically different mix or even a greater quantity of the desired platforms and capabilities. This is the premise underlying the strategic approach of the National Aeronautics and Space Administration (NASA) under the leadership of Daniel Goldin. See McCurdy's *Faster, Better, Cheaper*. The foundation of this approach is the nonlinear relationship between cost and complexity in the acquisition of complicated systems. See Bearden, "Complexity-Based Risk Assessment of Low-Cost Planetary Missions," 371–79.

25. DOD, "DOD Releases Fiscal 2013 Budget Proposal."

26. DOD, "Summary of the DOD Fiscal 2013 Budget Proposal."

27. The aerial refueling function is the exception. As a pure enabler, it fulfills a purpose only in relation to another platform. The E-3 AWACS, on the other hand, is independently capable of providing air surveillance to operational elements outside the closed system shown.

28. USAF, "B-2 Spirit."

29. National Air and Space Intelligence Center, *Ballistic and Cruise Missile Threat*, 14.

30. This section treats interdependence as a static phenomenon. Recall, however, that interdependence and adaptation are necessary and sufficient conditions for coevolutionary behavior. These behaviors are addressed in the sections that follow.

31. Note that the adaptation of force structure is not an autonomic evolution like that of organisms. Recall Thomas Hughes's notion of feedback in the evolution of large technological systems: "A crucial function of people in technological systems, besides their obvious role in inventing, designing, and developing systems, is to complete the feedback loop between system performance and system goal and in so doing to correct errors in system performance." Thus, the agency associated with force structure adaptation is human, though this analysis considers the human element as outside the force structure itself. Hughes, "Evolution of Large Technological Systems," 54.

32. Hanson, *War Like No Other*, 137.

33. Biddle, *Rhetoric and Reality*, 227.

34. Peattie, *Sunburst*, 172.

35. Overy, *Air War*, 93–94.

36. Note that describing each platform as optimized in some sense for one mission area does not imply that it has no capability in the other. That is, an air-dominance platform may have some capability to perform a strike mission, and a strike platform may have some air dominance capability.

37. The approach described here is fundamentally threat-based in its underlying assumptions. Writing in 2005, Sharon S. Caudle, an analyst with the Government Accountability Office, provides an apt description of threat-based planning. "[The] DoD [has] used threat-based planning since [it] instituted the Planning, Programming, and Budgeting System in 1962. However, threat-based planning meant strong response to a few situations while largely ignoring all other potential challenges. DoD's threat-based approach and illustrative official planning scenarios for major theater wars served as specifications, defining necessary and sufficient characteristics of the force structure." Caudle, "Homeland Security Capabilities-Based Planning," 2.4. Caudle and others attempt to highlight the differences between capabilities-based and threat-based planning. This difference as it relates to the Air Force and the force structure

problem is discussed further in chapter 4. At this point, it is sufficient to note that a threat-based scenario is adequate to demonstrate the existence of nonlinearities in force structure.

38. Wylie, *Military Strategy*, 88. Wylie also indicates that the functions of the Army, Navy, and Marine Corps are qualitatively different in this regard, leading to methodological tension in the description and analysis of force structure across the services.

39. In this context, elementary indicates that the methods used are those to which a student would be exposed in an undergraduate course in probability and statistics. For reference, the techniques and properties of probability used here are covered in Blum and Rosenblatt, *Probability and Statistics*, 47–99.

40. To keep the model parsimonious, all targets are considered equivalent with respect to the lethality of attacking aircraft; that is, the target set is perfectly homogeneous. This parameter varies according to the type of attacking aircraft, of course, but the model description is, at this point, general and applies equally to each aircraft type. The aircraft types differ only in the parameter values.

41. This assumption is problematic and difficult to substantiate. If this assumption is invalid, the interdependence of events A and G would introduce systemic nonlinearities via the scenario itself, however. Since the intent here is to demonstrate and elucidate the nonlinearities induced by force structure interdependencies, the assumption is contextually appropriate.

42. As with the lethality parameter previously described, the adversary is considered to have only one type of air-based defensive system and one type of ground-based defensive system.

43. Technically, such a definition should include a piecewise component defining the probability as one for any density greater than one to ensure the formulation remains consistent with the laws of probability.

44. Note that this is the first time in the current model where an endogenous distinction is made between the behavior and performance of the two attacking platforms.

45. That is, it satisfies the conditions of additivity, proportionality, and certainty that define a linear system. Technically, to satisfy the conditions of a linear program, the decision variables—the number of each type of aircraft—should be permitted to assume fractional values as well (condition of divisibility). This is not the primary concern in the model described, however, and such an assumption may reasonably be made in many circumstances. Winston, *Operations Research*, 53–54.

46. For simplicity, assume that air-to-ground effectiveness is independent of the ground-based target. That is, strike targets and ground-based defenses would be equivalent with respect to their vulnerability to friendly attackers.

47. Note that this reduces the quantities $P(I_A)$ and $P(I_G)$ to unity, simplifying the probability model somewhat.

48. A typical next step would be to select from among the admissible force mixes—those in the feasible region—the one that optimizes some objective (e.g., minimum cost). This step is not necessary to demonstrate the salience of the assumption of linearity, however. Also, to include platform cost would incorporate additional nonlinearities into the system under investigation. See Lee, *Cost Analyst's Companion*.

49. The characteristic of increasing returns is an emergent phenomenon. The particular engagement curves used in this example are based on the cumulative distribution function for a gamma distribution. If x_1 represents the number of air-dominance platforms and x_2 represents the number of strike platforms, then the density function for a gamma distribution describing the engagement probability $P(E_1^A)$ is given by $g(x) = (x_1^{m-1}e^{-x/n})(\Gamma(m)n^m)^{-1}$, where the parameters m and n were defined to make the cumulative distribution consistent with the described desiderata—

specifically, m, $n > 0$, $m \propto x_1(x_1 + x_2)^{-1}$, and $n \propto (a_1\rho_1)^{-1}$. Similar expressions were developed for each of the remaining engagement probabilities. Blum and Rosenblatt, *Probability and Statistics*, 326.

50. Simon, "Architecture of Complexity," 467–82.

51. This type of emergence is often described as "more is different." Anderson, "More Is Different," 393–96.

52. Murphy, Payne, and VanDerWoude, "Strategy Alternatives," 1507–19. The other major considerations involve the value structure of the defender and the surveillance strategy employed (ibid.)

53. The Air Force has transitioned to calling systems like the MQ-1, MQ-9, RQ-4, etc., remotely piloted rather than unmanned to reflect the fact that these systems are positively controlled by operators and require significant manpower to operate. For a discussion of this distinction, see Cooke, "Preface: Why Human Factors of 'Unmanned' Systems?," xvii–xxii. The nomenclature of unmanned aerial systems is used herein to emphasize the largely autonomous operation of the systems described.

54. USAF, *United States Air Force Unmanned Aircraft Systems Flight Plan, 2009–2047*, 34.

55. Note that the behavior of the individual UAS may not exhibit emergent properties, but the system of interest here is the collection of UASs and its aggregate behavior.

56. In this sense, the self-organized emergence discussed here is stronger than the weak emergence phenomenon of "more is different." Bar-Yam, "Mathematical Theory of Strong Emergence," 15–24.

57. The Air Force has extensively studied such systems. For example, see Corner, "Swarming Reconnaissance Using Unmanned Aerial Vehicles"; Price, "Evolving Self-Organized Behavior"; Slear, "AFIT UAV Swarm Mission Planning"; and Nowak, "Exploitation of Self Organization in UAV Swarms." Additional research on such systems includes Parunak, Purcell, and O'Connell, "Digital Pheromones for Autonomous Coordination of Swarming UAVs," 1–9; and Teague and Kewley, *Swarming Unmanned Aircraft Systems*.

58. Rogerson, "Quality vs. Quantity in Military Procurement," 83–84. Rogerson draws in particular on Scherer, *Weapons Acquisition Process*, and Gansler, *Defense Industry*. Note the similarity to the incentive-based characterization given here and the questions of collective costs and individual gains leading to emergent phenomena in the Tragedy of the Commons as Hardin describes in "Tragedy of the Commons," 1243–48, and as summarized in chap. 2.

59. Note the similarity to the multiple conceptual lenses Allison and Zelikow adopt in their analysis of the Cuban missile crisis. The two approaches Rogerson describes—the traditional explanation and his alternative—are analogous to the rational actor and organizational behavior models that Allison and Zelikow use in their book *Essence of Decision*, 13–254.

60. Office of the Secretary of Defense, *Military Transformation*, 15.

61. Cebrowski and Barnett, "American Way of War."

62. Senate Committee on Armed Services, *Report on Authorizing Appropriations for Fiscal Year 2010*, 32.

63. Michael Hoffman, John Reed, and Joe Gould, "Army: Working to Encrypt UAV Video Feeds," *Army Times*, 20 December 2009, http://www.armytimes.com/news/2009/12/army_uav_hack_122009w.

64. Scott Peterson, "Exclusive: Iran Hijacked US Drone, Says Iranian Engineer," *Christian Science Monitor*, 15 December 2011, http://www.csmonitor.com/World/Middle-East/2011/1215/Exclusive-Iran-hijacked-US-drone-says-Iranian-engineer-Video.

65. Pribyl, "Coevolution in Air Warfare," 1–2.

66. Ibid., 5.
67. Stephenson, "Revolution in Military Affairs," 39–41.
68. Welch, "Assessing the Value of Stealthy Aircraft," 48.
69. Ibid., 50–52.
70. The dynamic described is also an example of coevolutionary interaction between force structures and the Red Queen races that can result in such interactions.
71. Arthur, "Positive Feedbacks in the Economy," 92.
72. Dahm, *Technology Horizons*, vol. 1, 35.

Chapter 4

Complexity and Force-Structure Analysis

A (Very) Brief History of Applied Complex Systems

The science of complex systems is not a new one, though it has not always appeared under the label of *complexity* as that term is understood today and used here. For example, an early description of emergent phenomena appears in Adam Smith's description of an invisible hand operating to secure the public good from the sum of self-interested but interconnected and interdependent actors. According to Smith in his classic work *The Wealth of Nations*,

> By preferring the support of domestic to that of foreign industry, he intends only his own security; and by directing that industry in such a manner as its produce may be of the greatest value, he intends only his own gain, and he is in this, as in many other cases, led by an invisible hand to promote an end which was not part of his intention. Nor is it always the worse for the society that it was not part of it. By pursuing his own interest, he frequently promotes that of the society more effectually than when he really intends to promote it. I have never known much good done by those who affected to trade for the public good. It is an affectation, indeed, not very common among merchants, and very few words need be employed in dissuading them from it.[1]

Henri Poincaré joins Smith as a forerunner of the modern investigation of emergent phenomena in complex systems through his investigation of the character of chance in the early twentieth century. Poincaré claims that chance has three fundamental forms: statistically random phenomena, sensitivity to initial conditions, and perceptions of randomness induced by bounded rationality or analytic blindness.[2] In the first of these forms—exemplified by the kinetic theory of gases, the distribution of raindrops, and the mixing of fluids—the sheer number of variables and the profusion of minute causes leads to a state where the outcome is, in some sense, independent of the initial conditions and subject to description by statistical laws. In this form of chance, the specific history of the system is not important (i.e., the system does not exhibit path dependence), but the equilibrium properties of the whole constitute a form of emergence. "Thence come accidental errors," Poincaré explains, "and we attribute them to chance because their causes are too complicated and too numerous. Here again we have only little causes, but each of them would produce only a slight effect; it is by their union and their number that their effects become formidable."[3] The second form of chance, as discussed in chapter 1, is a precursor to the modern study of dynamic nonlinear systems and most memorably embodied in the butterfly effect. In both cases, the chance observed at a macroscopic scale is an emergent property of either the number of elements (i.e., more is different) or the inter-

dependent structure of the interactions undergone by elements of the system.[4] Regarding the third category of chance, Poincaré states that

> when we seek to foresee an event and examine its antecedents, we strive to search into the anterior situation. This could not be done for all parts of the universe and we are content to know what is passing in the neighborhood of the point where the event should occur, or what would appear to have some relation to it. An examination can not [*sic*] be complete, and we must know how to choose. But it may happen that we have passed by circumstances which at first sight seemed completely foreign to the foreseen happening, to which one would never have dreamed of attributing any influence and which nevertheless, contrary to all anticipation, come to play an important role.[5]

In this form, chance is an emergent phenomenon derived from the viewpoint adopted by the analyst. Recalling Bar-Yam's analogy in defining emergence, is one focused on the forest or on the trees?[6] Focus on one implicitly relegates the influences of the other to the category of exogenous influences outside the bounds of the model under investigation. While this is a characteristically different category of emergence, it is emergence nonetheless, and while Poincaré did not directly express his findings in the modern language of complexity theory, his study of chance was nonetheless a study of the foundations of complex systems.

Nobel laureate Herbert A. Simon more explicitly articulates some of the principles of complex systems in his 1962 essay "The Architecture of Complexity." In this work, Simon begins the modern study of complex systems as an independent discipline, noting that the theoretical developments "arose in the context of specific phenomena, but the theoretical formulations themselves make little reference to details of structure. Instead they refer primarily to the complexity of the systems under view without specifying the exact content of that complexity. Because of their abstractness, the theories may have relevance—application would be too strong a term—to other kinds of complex systems that are observed in the social, biological, and physical sciences." He then provides both a naïve definition of a complex system—"one made up of a large number of parts that interact in a nonsimple way"—perfectly compatible with more modern definitions of these systems and a working characterization of emergence. For complex systems, Simon observes that "given the properties of the parts and the laws of their interaction, it is not a trivial matter to infer the properties of the whole."[7] He also defines and investigates the relationship among complexity, hierarchy, and the evolutionary dynamics of complex systems and explores complex systems in terms of information theory. In short, he lays the foundation for much of the research that would follow in the field of complex systems.

Grappling with the concept of complex systems did not end with Simon's work. A decade later, Horst Rittel and Melvin Webber suggested that

> the search for scientific bases for confronting problems of social policy is bound to fail, because of the nature of these problems. They are "wicked" problems, whereas science has developed to deal with "tame" problems. Moreover, in a pluralistic society, there is nothing like the undisputable public good; there is no objective definition of equity; policies that respond to social problems cannot be meaningfully correct or false; and it makes no sense to talk about "optimal solutions" to social problems unless severe qualifications are imposed first. Even worse, there are no "solutions" in the sense of definitive and objective answers.[8]

Organizational theorist Russell L. Ackoff echoes Rittel and Webber's characterization of wicked problems: "No problem ever exists in complete isolation; every problem interacts with other problems and is therefore part of a set of interrelated problems."[9] Ackoff describes these interrelated systems of problems as "social messes." While neither of these examples uses explicit language related to complexity theory as considered here, the parallels are clear, and the problems or messes they describe occur within systems that neatly fit the definition of a complex adaptive system.

This growth in the field of complex systems continued and achieved a tipping point of sorts with the founding of the Santa Fe Institute (SFI) in 1984, a research organization formed "to tackle the great, emerging syntheses in science—ones that involve many, many disciplines."[10] As Geoffrey West, a physicist and former SFI president, states, "Complexity science and the SFI-style interdisciplinary research . . . are now hyped. Everywhere. Every university and every research funding agency talks about how the problems of the world are complex. And they all have at least one program in complexity."[11] One can now find the ideas of complexity theory in areas as diverse as the history of technology, ecology, evolutionary biology, economics, political science, and others.[12]

Complexity and Military Theory

Though not mentioned in the brief time line described above, the realms of national security, warfare, and the military have not been exempt from the application of complex-systems thinking in explicating their respective characters. In fact, the language of complex adaptive systems has had a profound impact on the theoretical framework underpinning security and military studies. For example, writing about the issues of national strategy and policy formulation at the end of the last century and in the aftermath of the Cold War, Steven R. Mann claimed that "a revolution of unfrequented scale is taking place that will transform strategic thought in ways unimagined. The bittersweet truth is that this has little to do with the 'new world order' set to follow the end of the Cold War and the success of Desert Storm. The true revolution in progress is

a scientific one, and its effects will change the pattern of both warfare and strategic thought."[13] He exploits Per Bak's concept of self-organized criticality—the idea that "large interactive systems perpetually organize themselves to a critical state in which minor events start a chain reaction that can lead to catastrophe" and that "composite systems never reach equilibrium but instead evolve from one metastable state to the next"[14]—to describe a framework for reconceiving strategic thought for national policy.[15] Further, somewhat more technical work applying the ideas of self-organized criticality to the theory of international relations—and by extension to the formation of national policy to interact with the international environment—has shed light on such phenomena as efforts to manage electoral stability (with lessons for states seeking to export and inculcate democratic norms) and the difficulty in predicting even the most monumental political events.[16] Others have applied the concept of self-organized criticality to explicate the international system along axes relevant to an understanding of the military problems of national security. For example, Roberts and Turcotte have analyzed the frequency-intensity characteristics of wars and demonstrated scale-free behavior for international conflict consistent with the predictions of self-organized criticality.[17] The implications of such findings are profoundly important in characterizing and scoping expectations regarding the relative frequency and intensity of conflict. The corollary implications for force structure are equally profound, if for no other reason than the scale-free behavior of such relationships illuminate the environment—one containing a relatively high incidence of extreme events—for which force structures are developed.[18]

This recognition of the security environment as a complex system has led various thinkers to postulate approaches for interacting with such an environment and developing strategies or plans for doing so. For example, Everett Dolman expends considerable effort in explaining the concepts of adaptation, emergence, chaos, and complexity as they relate to the purpose and process of formulating military strategy.[19] This discussion culminates with a quote from complexity theorist John Holland: "There's no point in imagining that the agents in the system can ever 'optimize' their fitness, or their utility, or whatever. The space of possibilities is too vast; they have no practical way of finding the optimum. The most they can ever do is to change and improve themselves relative to what the other agents are doing."[20] Harry R. Yarger, a professor at the US Army War College, relates this depiction of complex systems to the strategic environment:

> As a complex system, the strategic environment is interactive and adaptive because the states and actors have the capacity to respond individually and collectively (in a myriad of bilateral and multilateral relationships) to new challenges to the relationships and

> structures that provided stability in the past. When this balance is lost, the states and actors seek to self-organize their patterns of behavior into new patterns intended either to restore the former equilibrium or to obtain changes favorable to their interests. As in any complex system, to do this they must accommodate change, changing or responding in ways that provide for success in the new environment. At the same time, continuities with the past remain and are embedded in the emergent order.[21]

In the preceding quote from Holland one finds a potential intellectual source—and in Yarger an intellectual echo—of Dolman's nuanced definition of strategy. Dolman views strategy "in its simplest form, [as] a plan for attaining continuing advantage. For the goal of strategy is not to culminate events, to establish finality in the discourse between states, but to influence states' discourse in such a way that it will go forward on favorable terms."[22] Clausewitz would no doubt approve of these theories. It was Clausewitz, after all, who remarked that "even the ultimate outcome of war is not always to be regarded as final. The defeated state often considers the outcome merely as a transitory evil, for which a remedy may still be found in political conditions at a later date."[23]

Dolman and Yarger are not the first to conceive of the problems of security and warfare as complex problems and to construct a theoretical framework for strategic interaction with the environment through military means. Indeed, Alan Beyerchen has argued convincingly that the eighteenth-century masterwork of Carl von Clausewitz "is suffused with the understanding that every war is inherently a nonlinear phenomenon, the conduct of which changes its character in ways that cannot be analytically predicted" and that "in a profoundly unconfused way he understands that seeking exact analytical solutions does not fit the nonlinear reality of the problems posed by war."[24]

Beyerchen illustrates Clausewitz's view through numerous passages from *On War*. Perhaps the most evocative of these is the Clausewitzian concept of "war as a paradoxical trinity—composed of primordial violence, hatred, and enmity, which are to be regarded as a blind natural force; of the play of chance and probability within which the creative spirit is free to roam; and of its element of subordination, as an instrument of policy, which makes it subject to reason alone."[25] Clausewitz compares these three poles to magnets, between which a theory of war must maintain a balance. Beyerchen points out, however, that Clausewitz would no doubt have been aware of the emerging science surrounding electricity and magnetism in his day and the startling behavior of a pendulum suspended between three magnets[26]—one of the canonical representations of a chaotic, nonlinear, dynamical system intimately related to the so-called three-body problem.[27] He further comments that "if this metaphor can bear the burden of my contention, *On War* ought to be filled with insights

intended to identify and cope with nonlinearities. Clausewitz ought to display a deep and abiding concern for unpredictability and complexity, and consequently to search for ways to express the importance of such matters as context, interaction, effects disproportionate to their causes, sensitivity to initial conditions, time-dependent evolutionary processes, and the serious limitations of linear analysis."[28] Beyerchen enumerates many examples of these characteristics in Clausewitz's analysis, especially as they relate to unpredictability of the system of war—unpredictability deriving from adaptive interaction, friction, and chance in all its varieties.[29]

Clausewitz identifies interaction as one of the fundamental sources of systemic unpredictability in warfare. Perhaps a general model illustrating purposeful interaction with the environment most familiar to modern military audiences is that of John Boyd's so-called OODA loop, where OODA is an acronym for the sequence observe, orient, decide, and act. Figure 11 displays a full schematic of the cybernetic control process Boyd describes. Osinga provides a synopsis of the OODA loop:

> Observation is the task that detects events within an individual's, or group's, environment. It is the method by which people identify change, or lack of change, in the world around them. While it is not the sole basis for Action, it is a primary source for new information in the behavioral process. Note, however, he stresses "how orientation shapes observation, shapes decision, shapes action, and in turn is shaped by the feedback and other phenomena coming into our sensing or observing window." Without the context of Orientation, most Observations would be meaningless. Boyd is particularly detailed about Orientation. To survive and grow within a complex, ever changing world of conflict it is necessary to have insight and vision, focus and direction, he had stated earlier. To that end we must effectively and efficiently orient ourselves; that is, we must quickly and accurately develop mental images, or schema, to help comprehend and cope with the vast array of threatening and non-threatening events we face. This image construction, or orientation, is nothing more than the process of destruction (analysis) and creation (synthesis) he discussed in his briefings. It is how we evolve.[30]

Boyd's representation of the decision-making process and briefings of his ideas reflect his view that a purposeful and adaptive adversary is the dominant element of an individual's interaction with the environment.[31] However, figure 11 (and the simplified diagram more commonly seen in descriptions of Boyd's theories) might seem to imply that the environment is not comprised of distinct volitional actors undergoing similar transformations.[32] Rather, the implication is that while an actor interacts with the environment, the environment itself is not interacting with the actor in a purposeful way. Thus, figure 12 presents a more appropriate model. This simplified model supplements figure 11 and makes explicit the volitional interaction of agents in the environment.

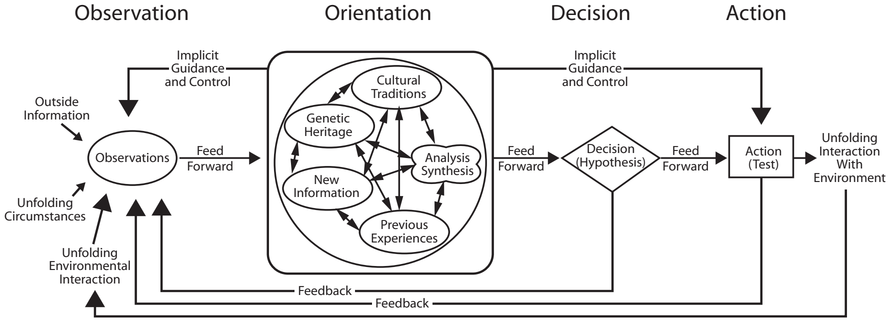


Figure 11. OODA loop. (Adapted from J. R. Boyd, "The Essence of Winning and Losing," unpublished briefing slides, 1996, Project on Government Oversight: Defense and the National Interest website, http://dnipogo.org/john-r-boyd.)

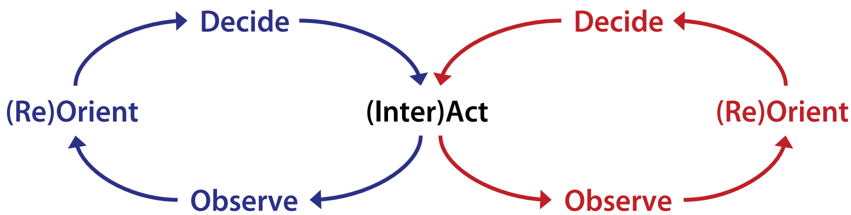


Figure 12. Interacting OODA loops

This depiction makes explicit the uncertainties Clausewitz describes and the coevolutionary nature of the interactive problem. For Clausewitz, war is not "the action of a living force upon a lifeless mass (total nonresistance would be no war at all) but always the collision of two living forces. The ultimate aim of waging war, as formulated here, must be taken as applying to both sides. Once again, there is interaction. So long as I have not overthrown my opponent I am bound to fear he may overthrow me. Thus I am not in control; he dictates to me as much as I dictate to him."[33] Of particular importance is the notion that one does not (and cannot) directly observe the orientation and intent of an adversary; one can only infer these factors based on (imperfect) observation. In any case, Boyd's own words underline his conception of the OODA loop as a model for interaction in a complex adaptive system. He remarks that the major ideas of his presentations on the OODA loop and related observations "represent an evolving, open-ended, far from equilibrium process of self-organization, emergence, and natural selection."[34]

This complexity-based approach to military action—following a path from Clausewitz through modern scientific thought—has influenced the US military. The United States Marine Corps' view of command and control, for example, is shaped by an explicit characterization of warfare and the military instrument as complex systems in precisely the same technical sense used here:

> Military organizations and military evolutions are complex systems. War is an even more complex phenomenon—our complex system interacting with the enemy's complex system in a fiercely competitive way. A complex system is any system composed of multiple parts, each of which must act individually according to its own circumstances and which, by so acting, changes the circumstances affecting all the other parts. A boxer bobbing and weaving and trading punches with his opponent is a complex system. A soccer team is a complex system, as is the other team, as is the competitive interaction between them. A squad-sized combat patrol, changing formation as it moves across the terrain and reacting to the enemy situation, is a complex system. A battle between two military forces is itself a complex system.[35]

Further, for the Marine Corps, the intellectual point of departure framing its doctrinal approach to interacting with and shaping this fiercely competitive environment is John Boyd and OODA.[36]

Boyd is not the sole source of inspiration for the explicit application of complexity theory to military questions. Andrew Ilachinski, an analyst with the Center for Naval Analysis, is another force in this arena. When the commanding general of the Marine Corps Combat Development Command requested an inquiry into the applications of complexity theory for the problems of land warfare, Ilachinski produced perhaps the most complete technical assessment of the utility of complexity theory for the military to date.[37] He concludes that "the concepts, ideas, theories, tools and general methodologies of nonlinear dynamics and complex systems theory show enormous, almost unlimited, potential for not just providing better solutions for certain existing problems of land combat, but for fundamentally altering our general understanding of the basic processes of war, at all levels. Indeed, the new sciences' greatest legacy may, in the end, prove to be not just a set of creative answers to old questions but an entirely new set of questions to be asked of what really happens on the battlefield."[38] Ilachinski offers a series of detailed observations for the applicability of complex systems theory as a general metaphor for warfare, a shaping mechanism for policy and strategy, a mechanism for assessing the validity of models for conventional conflict, and so forth.[39] He ends his work with a series of nine open questions designed to establish a research agenda for complexity and the military:

1. Are there measures of combat complexity?
2. Can patterns of observed chaotic data be exploited?
3. What is the appropriate phase space description for combat?

4. Can the chaos of combat be controlled or tamed?
5. What are the optimal strategies for adaptation on the battlefield?
6. What role does the psychology of the individual combatant play in shaping the combat process?
7. How complex must a combat system be in order for it to be amenable to the tools of complex systems theory?
8. How can one quantify the true value and nature of information on a battlefield?
9. Does the presence of fractals in combat point to something fundamental?[40]

A decade after Ilachinski's groundbreaking work appeared, Alex Ryan summarized the progress in addressing these questions. He notes, for example, that advances in the measurement of complexity in combat have been slow, the assertion of a deterministically chaotic (rather than stochastic) character for combat has yet to be demonstrated, the high dimensionality of the combat environment prevents substantial progress on the third question, and military applications for chaotic control remain elusive.[41] Ryan further describes three realms of warfare in which the notions of complexity theory seem to have the greatest potential for fruitful application: maneuver warfare, network-centric warfare, and irregular warfare. The value of complex-systems thinking in the study of maneuver warfare is demonstrated in the Marine Corps' application of Boyd's ideas. With respect to network-centric warfare, the link to complexity is equally explicit in the language used by its proponents. For example, Arthur Cebrowski and John Garstka describe self-synchronization—a central aspect of network-centric warfare—as "the ability of a well-informed force to organize and synchronize complex warfare activities from the bottom-up. The organizing principles are unity of effort, clearly articulated commander's intent, and carefully crafted rules of engagement."[42] With respect to irregular warfare, Ryan contends that "because the dynamics of irregular warfare are attracted towards increasing fine scale complexity, complex systems provide a more appropriate paradigm than traditional OR [operations research], which due to its origins in large scale conflict in World War II, emphasizes the importance of coordination to optimize large scale effects."[43] All of these have the potential for significant effects on the problems of force-structure analysis, but perhaps the most directly applicable is the series of advances made with respect to Ilachinski's last question. In particular, work by Michael Lauren and others develops new mathematical models for the representation of attrition in combat based on scale-free or fractal behavior. According to Lauren, "This approach solves many of the known problems

with conventional combat equations, which both fail to explain the power laws observed in combat data, and to explain the outcomes of many battles."[44] These novel approaches to the modeling of attrition are addressed again later.

The ideas of complexity theory as described above have not been simply theoretical in their influence on the US military. The effects on doctrine have already been noted. In addition, these concepts now play a pivotal role in the planning process at the operational and strategic levels of warfare, have shaped modern evaluations of historical battles and the lessons to be drawn from them, and influenced thinking about the process of targeting complex adaptive systems such as terrorist networks.[45] Gen James N. Mattis presents perhaps the most striking and direct example of applying complex systems theory to the military. As the US Joint Forces Command commander, he directed that "USJFCOM will no longer use, sponsor, or export the terms and concepts related to EBO [effects-based operations], ONA [operational net assessment], and SoSA [System-of-Systems Analysis] in our training, doctrine development, and support of JPME [joint professional military education]." Quoting Justin Kelly and David Kilcullen, Mattis stated that "'chaos makes war a complex adaptive system, rather than a closed or equilibrium-based system,' which makes predicting, and then assessing, how physical actions cause behavioral changes a significant challenge."[46]

The Analytic Gap

The preceding discussion has made abundantly clear the applicability of complex-systems theory to militarily critical questions. This relevance ranges from Clausewitz's theories on the underpinnings of war to the approach that today's military professionals take in planning for and executing operations. It seems a truth universally acknowledged that the international environment in general and the battlefield in particular are complex, chaotic environments populated with a diverse array of adaptive adversaries seeking advantage. For the United States Air Force, however, complexity theory has not made significant inroads in a key area. Specifically, the community of force-structure analysts in the Air Force—charged with assessing and recommending the capabilities and associated quantities that the Air Force needs to meet the national security demands placed on it—persists in treating force structure as a simple system. This mind-set continues despite the fact that, as argued in chapter 2, the force structure under examination is clearly a complex adaptive system. Such an assertion requires support, of course, and the balance of this chapter deals with the evidence. This evidence is divided into four basic, inter-

related categories: time lines, scenarios, measures and models, and inferential evidence from professional journals.[47]

A force structure is a complex adaptive system. That is, it is comprised of diverse, interdependent, adaptive elements interacting nonlinearly and exhibiting systemic behaviors including emergence, coevolution, and path dependence across multiple scales. The notion that a force structure coevolves with its environment implies that it transforms over time. Further, it is not simply the US force structure that evolves over time as a function of environmental, circumstantial, and volitional factors. Every other force structure comprising (a portion of) the environment evolves similarly, each seeking its own advantage. The force-structure-analysis community in the Air Force, however, almost universally fails to examine these transformations over time. Rather, it tends to address or assess force structure in the context of two narrowly prescribed time frames. The first of these, the midterm, is generally at the end of the current Future Years Defense Program (FYDP). The long-term period is placed two full FYDPs beyond that, approximately 20 years in the future. The transformation of the force structure in the intervening years and its relationship to the force structures of potential adversaries is essentially unexamined.[48] More precisely, the relative performance of the respective force structures between the mid- and long-term assessment time frames is an implicit interpolation between these points in time.[49] This assumes that the force-structure system remains in (dynamic) equilibrium throughout the intervening FYDP periods. Such an assumption is problematic, however, for complex adaptive systems.

Complex adaptive systems are subject to what paleontologists Stephen Jay Gould and Niles Eldredge first described as punctuated equilibrium, a phenomenon in which long periods of (dynamic) equilibrium or stasis in the fossil record are followed by periods of rapid or even explosive change.[50] While Gould and Eldredge limit their discussion to the fossil record and the evolution of biological species, similar patterns have been described in phenomena as diverse as avalanches, the economy, and ecosystems.[51] Of greater interest, however, is the behavior of technological evolution and innovation since this relates directly to the temporal behavior of the physical manifestations of force-structure technology. As Eric Beinhocker says,

> Technology evolution is not a mere metaphor. It is the result of humankind's deductive-tinkering search through the near-infinite possibilities of Physical Technology [PT] space. The nature of the process of differentiation, selection, and replication in this substrate is different from that of biology, but it is an evolutionary process nonetheless. This means that PT evolution follows the same general laws that apply to other evolutionary systems. It also means that PT evolution exhibits behaviors common to other evolution-

ary systems such as the tendency of innovations to spur further innovations, and the punctuated-equilibrium nature of technology change."[52]

Revolutions in military affairs and military revolutions provide concrete and well-studied examples of punctuated equilibrium as the result of these evolutionary processes in military force structure. Murray describes the former as events that bring with them "such systemic changes in the political, social, and cultural arenas as to be largely uncontrollable, unpredictable, and above all unforeseeable" and "recast the nature of society and the state as well as military organizations." RMAs, on the other hand, are smaller phenomena that alter the conduct of war within a given framework rather than altering the framework itself. In an RMA, "military organizations must come to grips with fundamental changes in the political, social, and military landscape; they innovate and adapt to—in some cases foreshadow—revolutionary changes." Murray points to four military revolutions (creation of the modern nation state, the French Revolution, the Industrial Revolution, and World War I) and 21 RMAs (e.g., the longbow, gunpowder, blitzkrieg, carrier warfare, people's war, etc.) spanning 700 years as evidence of the discontinuous progress of military evolution.[53] Each of these revolutions punctuates to a greater or lesser degree the equilibrium of the military dynamics of its time and illustrates the complex dynamics of military force structure.

Thus, the explicit or implicit treatment of the complex adaptive system of physical force structure as a system in (dynamic) equilibrium or stasis is problematic on its face. Further, the failure to anticipate the possibility of rapid, unforeseen changes in the relative capabilities of opposed force structures in the years between assessment time frames is systemically susceptible to "Black Swan" phenomena.[54] This gap, then, represents a significant issue in terms of unexamined, unquantified, and unqualified risk for the recommendations force-structure analysts have produced for the Air Force.

The issue of scenarios is similar to that of time lines in that both presume a predictive fidelity regarding the future that a force structure faces. In the case of time lines, the presumption is associated with physical technology's stable trajectory over the course of 15 years. This trend leads, in part, to the presumptions associated with force planning via a limited number of carefully prescribed, threat-based scenarios.[55] These scenarios serve as the requirement against which the utility of a force structure will be measured in the process of force-structure analysis, and they serve as the basis of comparison for alternative force structures. In any given year, however, this analysis involves as few as four to five major scenarios (including those covering major theater war, irregular war, and homeland defense in the two time frames described

earlier).[56] It takes little effort to reveal how narrow is the resulting characterization of the potential scenarios a force structure may face. Consider a scenario in which the adversary's objective is fixed. Allowing for factors such as variability in the capabilities of each adversary faced; the myriad possibilities for basing, overflight, and support among regional actors; or the amount of strategic warning received prior to the commencement of hostilities, the space of possible standalone scenarios is effectively infinite. Many of these might be subsumed under some subset of most-dangerous scenarios, but the range of possibilities for scenario variation with the potential to impact force-structure evaluation remains enormous. Add to this the possibility of concurrency of scenarios, and the realm of conceivable exigencies grows multiplicatively.[57] The relatively static character of the scenarios used from year to year exacerbates these limitations. Scenarios evolve only incrementally since force-structure analysts tend to repeatedly use those from previous analysis cycles rather than create new ones.[58]

The resulting lack of diversity induced by the narrowly predictive nature of the scenarios used for analysis creates a class of unexamined risk and increases the potential for surprise.[59] Nassim Nicholas Taleb observes that "governments make forecasts; companies make projections; every year various forecasters project the level of mortgage rates and the stock market at the end of the following year. Corporations survive not because they have made good forecasts, but because . . . they may have been the lucky ones." Of particular importance here, he also notes the fundamental difference between corporations and governments: "Corporations can go bust as often as they like. . . . Government is a more serious business and we need to make sure we do not pay the price for its folly."[60]

Predictability is problematic in complex adaptive systems, and the dearth of scenarios for the evaluation of force structure is therefore an area of risk. This risk is particularly acute given the path-dependent behaviors that complex adaptive systems—including force structure—exhibit. Should a series of decisions derived from or informed by scenario-based analysis lead to a particular instantiation of force structure, that force structure may be difficult to change when flawed predictions manifest themselves. For example, one of the characteristics implicit or explicit in any scenario is the technical capabilities of the respective players. If the capture of an RQ-170 by Iran should lead to a proliferation of stealth and counterstealth technologies, what will be the impact to the efficacy of a US force structure critically dependent on stealth?[61] Can the US Air Force deviate from a force-structure trajectory driven by a strategy that acquires smaller numbers of highly advanced aircraft at great expense when those aircraft are compromised?

The third area demonstrating a disconnect between the nature of force structure as a complex adaptive system includes the measures and models used in force-structure analysis. Consider the issue of measures associated with force structure. No single variable or measure can describe fully the relative value of that force structure vis-à-vis all other possible force structures. Moreover, the variables that describe a force structure are often in competition with one another. Take, for example, the competing metrics/demands of exploration (reconnaissance) and exploitation (surveillance) in an ISR force structure. One can procure systems designed to exploit a given target or targets (e.g., Predator using full-motion video systems) and others designed to explore a wide area searching for targets (e.g., JSTARS), but a force structure that concentrates on one to the exclusion of the other is likely problematic.[62] It is this principle that leads Paul Davis to state that "when making assessments in capability analysis, multiple objectives are customary." He goes on to note, however, that "this may seem straightforward, but defense analysis too often focuses instead on what amounts to a single objective."[63] Very often in force-structure analysis in the Air Force, this concentration on a single objective is even more explicit than Davis suggests.

One of the primary force-structure analysis tools the Air Force uses is the Combat Forces Assessment Model (CFAM), "a large-scale, linear program (LP) designed to provide decision makers with an analytical tool for determining the impact of budget, attrition, force structure, targeting decisions, and munitions inventories on war fighting capabilities."[64] Note that—with regard to CFAM and its application to force-structure analysis—an almost total fixation exists on the relationship between cost and time required to achieve a collection of attrition-based objectives. The most common practice is to use CFAM to minimize the measure of time given a fixed available budget.[65]

In addition to this issue of metrics, the Air Force's use of tools like CFAM is representative of at least three additional difficulties in the analysis of force structure as a complex adaptive system (beyond those issues contingent on the question of time lines described above). The first of these relates to CFAM's mathematical underpinnings. As noted, CFAM is a linear program. Therefore, its use in force-structure analysis makes the explicit assumption that a force structure in operation is a linear system.[66] It has been shown here, however, that such an assumption is demonstrably problematic.

The second relates to the assumptions underlying the attrition model based on the work of Frederick William Lanchester.[67] Lanchester's model as a representation of attrition in combat has drawn considerable criticism. Perhaps the most telling may be Joshua Epstein's observation that "surely one's force-planning methods, while appropriately aggregate, transparent, and succinct, should not

mathematically preclude phenomenon that are ubiquitous and essential to the very process under study or mathematically presume other phenomena (e.g., perfect concentration) for which counterexamples are equally abundant. The Lanchester equations and their contemporary extensions simply do not satisfy those minimum empirical standards."[68] One of the empirical observations of combat-attrition data the Lanchester equations do not (and cannot) reflect, for example, is the emergent phenomenon of power-law attrition (as opposed to the continuous attrition Lanchester implies).[69] CFAM and other combat models that the Air Force uses in force-structure analysis are generally based on this attrition model (or a version of it), a practice inconsistent with force planning for complex systems in dynamic, complex environments.

Third, CFAM is designed to compute mathematically optimal performance within a scenario/conflict. This mathematical approach is inconsistent with the complex-adaptive nature of force structure. For many problems—those in which the fitness landscape is fixed—this approach is perfectly reasonable, and successful applications of linear and nonlinear optimization abound. For complex adaptive systems, however, the performance or fitness of elements in the system is best characterized as residing on what Scott Page calls a dancing landscape.[70] In such cases, a point solution for an optimal force structure projected for some future date has no meaning, and optimizing its performance adds little value. This is precisely the futility identified by John Holland and discussed in chapter 2.[71] These point solutions, however, are just those comprising the output of the force-structure analysis that informs subsequent force planning.[72]

The final category of support is taken from a review of articles published between 1994 and 2011 in *Military Operations Research*, a "peer-reviewed journal of high academic quality" that "publishes articles that describe operations research (OR) methodologies and theories used in key military applications."[73] While this journal deals with a broader array of technical issues than the narrow question of force-structure analysis for the Air Force, the absence of evidence treating force structures as complex adaptive systems in this broader milieu will imply a similar lack with respect to the narrower field.

In fact, the analytic principles related to the study of complex systems as applied to military matters in general and force structure in particular are not completely absent from the pages of *Military Operations Research*. For example Michael Lauren's observations regarding issues associated with traditional methods for describing attrition on dispersed battlefields via the Lanchester equations and his description of alternate, fractal methods were published in the journal in 2002.[74] As noted above, though, these observations have not found their way into the process of force-structure analysis as used by the Air

Force. Neither have they apparently affected the inclusion of Lanchester-based attrition methods, models, and analysis in subsequent issues of the journal.[75] One also finds research offering methods for dealing with systems-of-systems problems (problems that are interactively complex) with applications to force planning under conditions of uncertainty.[76]

While some academic and analytic inroads have been made with respect to the inclusion of methods for the analysis of complex adaptive force structure, however, significant gaps and conceptual disconnects remain. No article among the 16 volumes of *Military Operations Research* reviewed, for example, addresses the evolutionary nature of the force structure as it transforms over time. This gap is also reflected in the failure of any article in that span to treat opposing (or allied) force structures as components of a coevolutionary system. Optimization methods figure prominently in the literature presented by the journal, but these methods are designed either for the maximization (or minimization) of the performance of force structures across a variety of scenarios or within a given scenario.[77] Also, the contents of the journal fail to address diversity and path-dependent phenomena, and emergence appears only implicitly in the context with respect to a limited number of agent-based modeling experiments reported there.[78]

Notes

1. Smith, *Wealth of Nations*, bk. 4, chap. 2, par. 9.
2. Poincaré, *Foundations of Science*, 395–412.
3. Ibid., 402.
4. See, for example, Anderson, "More Is Different," 393–96.
5. Poincaré, *Foundations of Science*, 402.
6. Bar-Yam, *Making Things Work*, 27
7. Simon, "Architecture of Complexity," 467–68.
8. Rittel and Webber, "Dilemmas in a General Theory of Planning," 155.
9. Ackoff, *Redesigning the Future*, 21.
10. Waldrop, *Complexity*, 75.
11. Quoted in ibid., 365.
12. For accessible examples, see Arthur, *Nature of Technology*; Levin, *Fragile Dominion*; Kauffman, *Origins of Order*; Beinhocker, *Origin of Wealth*; and Jervis, *System Effects*.
13. Mann, "Chaos, Criticality, and Strategic Thought," 33.
14. Bak and Chen, "Self-Organized Criticality," 46. For more on the issue of self-organized criticality, see Bak, Tank, and Weisenfeld, "Self-Organized Criticality," 381–84; and Bak and Paczuski, "Complexity, Contingency, and Criticality," 6689–96. More recent work applies the theory of self-organized criticality to the theory of international relations.
15. Mann, "Chaos, Criticality, and Strategic Thought," 45–50.
16. Brunk, "Self-Organized Criticality," 427–45. A more general application of complexity theory—broader than the view given in the theory of self-organized criticality—and the at-

tendant implications for the theory of international relations are given in Bousquet and Curtis, "Beyond Models and Metaphors," 43–62.

17. More specifically, Roberts and Turcotte demonstrate an empirical parallel between the size-frequency relationship observed in warfare data, the so-called forest-fire model, and the observed size-frequency relationship in actual forest fires. They contend, "A war must begin in a manner similar to the ignition of a forest fire. One country may invade another country, or a prominent politician may be assassinated. The war will then spread over the contiguous region of metastable countries. Such regions of metastability could be the countries of the Middle East (Iran, Iraq, Syria, Israel, Egypt, etc.) or the former Yugoslavia (Serbia, Bosnia, Croatia, etc.). These are then the metastable clusters. In some cases, the metastable clusters could combine. Albania and Greece bridge the gap between the metastable clusters of the Middle East and the former Yugoslavia." Roberts and Turcotte, "Fractality and Self-Organized Criticality," 351–57. In this work, Roberts and Turcotte extend and refine the seminal research of Lewis F. Richardson. For example, see Richardson's articles "Frequency of Occurrence of Wars," 37–59, and "Variation of the Frequency of Fatal Quarrels," 523–46.

18. This approach to describing the future has a potential inductive fallacy since it assumes the past is a reasonable indicator for future behavior. For an extensive critique of such reasoning, see Taleb's *Black Swan*.

19. Dolman, *Pure Strategy*, 94–138.

20. Quoted in ibid., 138.

21. Yarger, *Strategy and the National Security Professional*, 33. It is not simply the dynamic character of the environment that characterizes the environment as complex. The notion that continuities with the past persist is a concise articulation of the concept of path dependence.

22. Dolman, *Pure Strategy*, 6. This is an interesting echo of Helmuth von Moltke, chief of the Prussian General Staff, who presided over Prussian victories against Austria in 1866 and France in 1870–71, and his definition of strategy. Moltke suggests that "strategy is a system of expedients . . . the translation of knowledge to practical life, the improvement of the original leading thought in accordance with continually changing situations." Moltke, *Moltke on the Art of War*, 124.

23. Clausewitz, *On War*, 80.

24. Beyerchen, "Clausewitz, Nonlinearity, and the Unpredictability of War," 61.

25. Clausewitz, *On War*, 89.

26. To support these claims and avoid an overly presentist interpretation of Clausewitz's characterization of warfare as nonlinear, Beyerchen relies on Paret's *Clausewitz and the State*.

27. Gleick, *Chaos*, 43–44; and Mitchell, *Complexity*, 21–22.

28. Beyerchen, "Clausewitz, Nonlinearity, and the Unpredictability of War," 72.

29. Ibid., 72–87.

30. Osinga, *Science, Strategy, and War*, 231–32.

31. Ibid., 189–233; Boyd, "Essence of Winning and Losing"; and Coram, *Boyd*, 334–39.

32. For example, see Marine Corps Doctrine Publication (MCDP) 6, *Command and Control*, 64; or Osinga, *Science, Strategy, and War*, 2. Robert Coram, one of Boyd's biographers, states, "The OODA Loop is often seen as a simple, one-dimensional cycle, where one observes what the enemy is doing, becomes oriented to the enemy action, makes a decision, and then takes action. This 'dumbing down' of a highly complex concept is especially prevalent in the military, where only the explicit part of the Loop is understood." Coram, *Boyd*, 334.

33. Clausewitz, *On War*, 77. Of note, Clausewitz uses this interaction to motivate what he calls the second extreme in his articulation of the *theoretically* unbounded construct for abso-

lute war—the maximum exertion of strength. In this case, one sees warfare as more of a complex adaptive system. In the quoted passage, Clausewitz cogently articulates the concept of the security dilemma in particular and path-dependent phenomena in general as they relate to exertion and the acquisition of material means in and for warfare.

34. Quoted in Osinga, *Science, Strategy, and War*, 232.

35. MCDP 6, *Command and Control*, 44. See also MCDP 1, *Warfighting*.

36. MCDP 6, *Command and Control*, 63–65.

37. Ilachinski, *Land Warfare and Complexity*, pts. 1 and 2.

38. Ibid., pt. 2, 2.

39. Ibid., 40–118.

40. Adapted from ibid., 123–26.

41. Ryan, "Military Applications of Complex Systems," 734–36.

42. Quoted in ibid., 738. Ryan includes in this discussion Antoine Bousquet's critique of network-centric warfare as an exemplar of complexity theory in application. Bousquet claims that "network-centric warfare . . . despite nods to chaos theory and complexity science, is found to be still largely in thrall to the principles of cybernetic warfare." Bousquet, *Scientific Way of Warfare*, 7.

43. Ryan, "Military Applications of Complex Systems," 739. This characterization relies on the work of Bar-Yam and the relationship between scale and complexity. See Bar Yam, "Multiscale Variety in Complex Systems," 37–45.

44. Lauren et al., "Art of War," 013121.1–.5.

45. For example, see *Art of Design*, student text, version 2.0; Reilly, "Design"; Leonard, "Clausewitz, Complexity, and Custer"; and Glenn, " 'Complex' Targeting."

46. Mattis, "USJFCOM Commander's Guidance for Effects-Based Operations," 107–8.

47. In a sense, the entire argument is inductive and inferential since it seeks to provide evidence for a negative conclusion.

48. Of itself, the notion of detailed force-structure analysis in a time frame 20 or more years into the future should be approached with healthy skepticism. The well-known empirical observations of Moore's Law (that the computing power for a chip doubles every 18–24 months, alternately stated as reducing size or cost by half in similar time, ceteris paribus), for example, would indicate that computational power will increase by a factor of over 1,000 in that span of time. See Kurzweil, *Age of Spiritual Machines*, 20–25. This theorem adds weight to the recommendation in chapter 4 that greater analytic attention should be focused on the evolutionary dynamics of force structure.

49. Dr. Jacqueline R. Henningsen (director, Air Force Studies and Analyses, Assessments, and Lessons Learned, Headquarters USAF, Washington, DC), interview by the author, 15 February 2012; and Maj Gen Jack Weinstein (director of programs, Office of the Deputy Chief of Staff for Strategic Plans and Programs, Headquarters USAF, Washington, DC), interview by the author, 15 February 2012.

50. Gould and Eldredge, "Punctuated Equilibrium Comes of Age," 223–27.

51. Bak and Chen, "Self-Organized Criticality," 46–53; Scheinkman and Woodford, "Self-Organized Criticality and Economic Fluctuations," 417–21; and Jain and Krishna, "Large Extinctions in an Evolutionary Model," 2055–60.

52. Beinhocker, *Origin of Wealth*, 259. For a complete discussion of the evolutionary nature of technology, see Arthur's *Nature of Technology*.

53. Murray, "Thinking about Revolutions," 70–73.

54. Taleb defines a "Black Swan" as "an event with the following three attributes. First, it is an outlier, as it lies outside the realm of regular expectations, because nothing in the past can convincingly point to its possibility. Second, it carries an extreme impact. Third, in spite of its outlier status, human nature makes us concoct explanations for its occurrence after the fact, making it explainable and predictable." See Taleb, *Black Swan*, xvii–xviii.

55. RAND analyst Paul Davis describes this form of planning as "an approach based on official scenarios for major theater wars that not only identified adversaries, but also laid out scenario details, such as warning time and roles of allies. . . . [The] DoD's routine analysis process had become so focused on these official scenarios, along with the official databases for running official models . . . it was as though the illustrative scenarios had become specifications serving to define both necessary and sufficient characteristics of the force structure." Davis, "Uncertainty-Sensitive Planning," 141.

56. Henningsen, interview.

57. Davis, "Uncertainty-Sensitive Planning," 146–51. Davis develops the concept of a scenario space and notes the general failure of the defense planning (i.e., force structure analysis) community to adequately assess the character of this space, a process he calls exploratory analysis under uncertainty. He offers possible approaches for such an assessment, but these remain outside the norm in force-structure analysis.

58. Henningsen, interview.

59. This limited, scenario-based approach implicitly characterizes the mid- and long-term future as predictable, an assumption already repeatedly discredited in this analysis.

60. Taleb, *Black Swan*, 180–81.

61. Herridge, "Iran Making Overtures to China."

62. This characterization of the competing demands of exploration and exploitation has wide applicability to complex systems in general. For example, see March, "Exploration and Exploitation in Organizational Learning," 71–87; or Kollman, "Rotating Presidency of the European Council," 51–74.

63. Davis, "Uncertainty-Sensitive Planning," 145.

64. Bennett, "Robust Multi-Scenario Optimization," 13.

65. Henningsen and Weinstein, interviews. Optimizing against other objectives is possible, but these approaches are somewhat unusual in their application to force-structure analysis. Note the echo of Wylie's assertions regarding analytical approaches to airpower discussed in chapter 3. Wylie, *Military Strategy*, 88.

66. That is, it satisfies the conditions of additivity, proportionality, certainty, and divisibility that define a linear system. Winston, *Operations Research*, 53–54. CFAM may also be used as a mixed integer program, removing the requirement for divisibility, but the other critical assumptions remain.

67. For Lanchester's original explication of his equations describing combat attrition, see his book *Aircraft in Warfare*, 46–50. Lanchester's system of coupled differential is described by $dB/dt = -rR$ and $dR/dt = -bB$. In these equations, R and B represent the sizes of the red and blue forces, respectively, at time t; the constant parameters r and b represent the effectiveness or firing rates of the red and blue forces. Note the similarity of this model to the Lotka-Volterra equations describing the interdependence of predator and prey in an ecosystem. They differ in the sense that Lanchester's mathematical description of the interaction between red and blue is linear.

68. Epstein, "Dynamic Analysis," 162.

69. For examples testing the empirical observation that attrition in war is represented by a power law distribution, see Small and Singer, *Resort to Arms*; and Clauset, Shalizi, and Newman,

"Power-Law Distributions," 661–703. For an explication of the emergence of the phenomenon of scale-free behavior from underlying dynamics, see Roberts and Turcotte, "Fractality and Self-Organized Criticality," 351–57; and Lauren et al., "Art of War," 013121.1–1.5. These describe attrition both within and across conflicts; one characteristic of a power-law relationship is that it is scale free in this regard.

70. Page, *Diversity and Complexity*, 93. These dancing landscapes are caused by the interdependencies between elements of the system, and they cause the Red Queen phenomenon previously discussed.

71. Recall that Holland wrote, "There's no point in imagining that the agents in the system can ever 'optimize' their fitness, or their utility, or whatever. The space of possibilities is too vast; they have no practical way of finding the optimum. The most they can ever do is to change and improve themselves relative to what the other agents are doing." Quoted in Dolman, *Pure Strategy*, 138.

72. Henningsen and Weinstein, interviews.

73. Military Operations Research (MOR) Society, "*MOR* Journal."

74. Lauren, "Fractal-Based Approach," 17–29. See also Speight, "Lanchester's Equations," 15–43.

75. For example, see Lucas and Dinges, "Effect of Battle Circumstances," 17–30; and Brown and Washburn, "Fast Theater Model," 33–45.

76. McInvale, McDonald, and Mahadevan, "System of Systems Approach," 31–46. Such methods represent an attempt to overcome the analytical difficulties associated with interactively complex, loosely coupled systems. See Jobbagy, "Effects-Based Operations," 90–95.

77. Recall that the Red Queen race and coevolution tend to render simple optimization conceptually problematic as a goal. Optimizing against performance is no longer (necessarily) appropriate, especially as it presupposes a capacity for predictive fidelity. However, optimizing adaptability and/or robustness is more appropriate in a complex adaptive system, where the efficacy of adaptability and robustness are measured in terms of capability.

78. For example, see Hill et al., "Some Experiments with Agent-Based Models," 17–28; and Kress, Baggesen, and Gofer, "Probability Modeling," 5–24.

Chapter 5

Recommendations and Conclusion

Two hypotheses and evidence for the veracity of each have been offered in the preceding chapters. Based on the foundation of a definition for complex adaptive systems, it was first argued that the material force structure of the United States Air Force is a complex adaptive system and exhibits all of the characteristic behaviors of such systems (e.g., coevolution, path, dependence, etc.). This was followed by the proposition that the prevailing paradigm in the community of force-structure analysts providing support for Air Force decision makers does not recognize the true character of the force-structure system under examination. This is not a surprising outcome, of course. As Steven Mann points out, "In the simplest sense, combat is mechanics. No surprise then that military strategy rests on a reductionist, mechanistic framework."[1] And just as military strategy rests on a reductionist, mechanistic framework, so does force-structure analysis. Unfortunately, war is not simple mechanics, as Clausewitz points out in the second book of *On War:*

> The essential difference is that war is not an exercise of the will directed at inanimate matter, as is the case with the mechanical arts, or at matter which is animate but passive and unyielding, as is the case with the human mind and emotions in the fine arts. In war, the will is directed at an animate object that reacts. It must be obvious that the intellectual codification used in the arts and sciences is inappropriate to such an activity. At the same time, it is clear that the continual striving after laws analogous to those appropriate to the realm of inanimate matter was bound to lead to one mistake after another. Yet it was precisely the mechanical arts that the art of war was supposed to imitate.[2]

The divide between the nature of force structures and the current conceptual paradigms undergirding their analysis (closed equilibrium systems, linearity, etc.) is not unbridgeable, however. Numerous opportunities exist for bringing force-structure analytic methods into alignment with the nature of the system to which they are applied. The opportunities fall into three basic categories: measures that describe a given force structure and allow comparison to other force structures, mental models and computational tools to facilitate the examination of force structures and the articulation of desired measures, and analysts to employ these analytic tools in support of force-structure planning and programming decisions. The following discussion of each category offers a road map for initial steps—each intended to provide long-term leverage at low cost—toward reconciling force-structure analysis in the Air Force with the complex adaptive nature of the phenomena.[3]

Measures

Prominent measures for the relative goodness of a given or candidate force structure typically focus on the performance of that force structure under prescribed circumstances (e.g., time to accomplish objectives and attrition suffered in the course of achieving those objectives), capability enumeration (e.g., in the context of joint capability areas), and cost. While these measures are vitally important in understanding force structure, they are simply inadequate in their characterization of a complex adaptive system facing an uncertain future. Four additional measures with the potential to profitably supplement these and enhance the understanding of force structure include diversity, robustness, flexibility, and adaptability.

Given that diversity is fundamental to the underlying character of complex adaptive systems, it is natural to consider the possibility that measures of diversity might contribute to an understanding of the dynamics of force structure. This does not imply that one should advocate for diversity for its own sake. Rather, it is important to study the relationship between diversity and advantageous outcomes and to use this study to inform force-structure analysis.[4]

Recall from chapter 2 the notions of diversity—specifically the Shannon entropy and Simpson diversity indexes—as applied to force structure. In that case, Shannon and Simpson diversity were computed for that portion of the projected 2012 force structure comprised of fighter and attack platforms. As has been observed repeatedly, however, a force structure does not exist solely at a single point in time; it has a past and a future, and the dynamics associated with movement through time matter in terms of the measures applied to the force structure. Thus, in figure 13, these computations were repeated in each year for which projected force structures were available (2012–21) and for extrapolations of the force-structure trends in the years 2022–40. What are the potential ramifications for the diminished diversity this figure shows? Why might diversity be important to a system? In the words of John Boyd, the simple answer is that diversity can contribute to the ability of a system "to shape and adapt to unfolding circumstances" and "survive on [its] own terms."[5] Diversity contributes to this capacity through a number of related mechanisms. These mechanisms then comprise the additional measures proposed above (flexibility, robustness, and adaptability).[6]

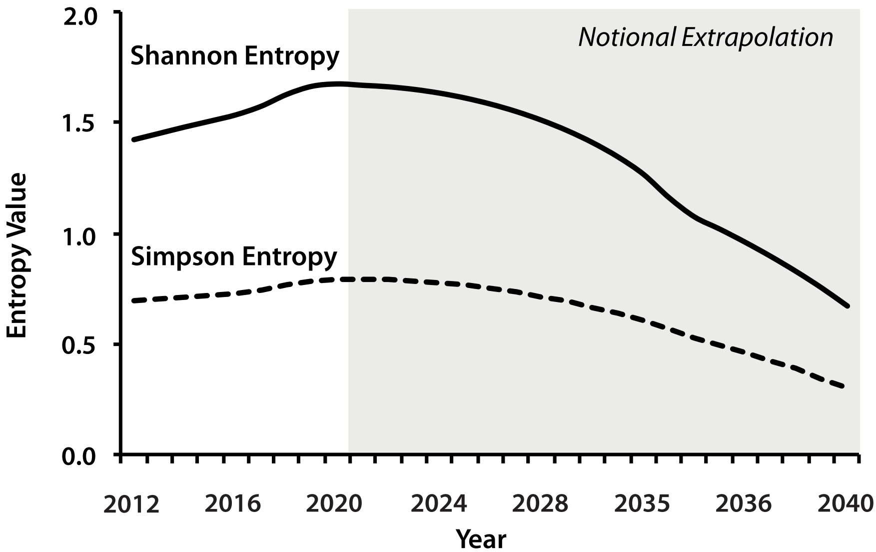


Figure 13. Fighter/attack diversity (2012–40). The data for 2012–21 comes from Headquarters USAF, "Air Force 30-Year Aviation Procurement Report Data Submission," 10 November 2010. For the period beyond 2021(shaded), the author used a naïve extrapolation of these data. This extrapolation applies the average rate of change for each platform type for the years 2012–21 uniformly in each subsequent year. When a platform is reduced to a force structure of zero, the extrapolation continues for the other platforms but is scaled to maintain a constant number of total aircraft from that point on.

In this context, the flexibility of a given force structure is defined as its capacity to accommodate or respond to a variety of scenarios.[7] Thus defined, the value of flexibility is summarized in the law of requisite variety first described by the cyberneticist W. Ross Ashby. If disturbances are possible in the environment (*D*), then the ability of a system to control the outcome—to shape and adapt to unfolding circumstances and survive on its own terms—is contingent on the responses available to the system (*R*). To reduce the variation in the outcomes that the disturbances can induce, increasing the number of responses available is necessary to counteract those disturbances. That is, according to Ashby, "the law of Requisite Variety [states that] only variety in *R* can force down the variety due to *D*; variety can destroy variety."[8] Ashby's disturbances are the scenarios to which a force structure might have to respond, and flexibility describes the potential of the force structure to shape and adapt to unfolding circumstances.[9]

The robustness of a force structure, on the other hand, refers to its sensitivity to changes in itself (including those an adversary induces).[10] The value of robustness in this sense, achieved via diversity and some associated redundancy, is eloquently described by ecologists Paul and Anne Ehrlich: "Ecosystems, like well-made airplanes, tend to have redundant subsystems and other 'design' features that permit them to continue functioning after absorbing a certain amount of abuse. A dozen rivets or a dozen species might never be missed."[11] This redundancy can take a quantitative or qualitative form. In the former, it is achieved via the duplication of identical elements (e.g., two identical fire extinguishers). In the latter, it is achieved by the presence or action of qualitatively diverse elements fulfilling the same function (e.g., although a bucket of water and a bucket of sand have different properties, both serve as fire extinguishers).[12] Tension exists between quantitative and qualitative redundancy (diversity). While it can increase robustness, the extreme of perfect redundancy (especially quantitative) in a cost-constrained system eliminates diversity of type. Similarly, the elimination of redundancy in pursuit of total diversity produces a system susceptible to single points of failure.[13] A second danger in redundancy is the creation of systems that may not degrade gracefully. Continuing the analogy of ecosystems and aircraft, while a dozen rivets or species may not be missed, "a thirteenth rivet popped from a wing flap, or the loss of a key species involved in the cycling of nitrogen, could lead to a serious accident."[14]

The notion of redundancy illustrated here illuminates two important considerations for complex adaptive systems and the characterization of redundancy: scale and keystones. At one scale (the individual rivet level), individual rivets exhibit redundancy; at another scale (collecting the wing flap rivets into a single group), this redundancy disappears. Similarly, at the scale of single organisms, an ecosystem may exhibit considerable redundancy. However, considering the ecosystem at the level of interacting species may reveal certain species biologists describe as keystone.[15] As with the keystone in an arch, removing these critical, nonredundant species can significantly impact the system's structure and function. So the scale at which a complex system is considered can greatly influence the description and understanding of it.[16]

While this discussion of robustness, diversity, and redundancy is couched primarily in terms of ecological systems, the application to created complex adaptive systems such as military force structures is clear. How robust is a force structure? If, for example, the F-22 is grounded for technical reasons, what are the impacts on the overall force structure's capacity to conduct necessary operations?[17] What is the impact on the flexibility of the force structure? How does this impact change over time? For example, consider figure 13. Is the result of grounding the F-22 greater in 2040 (when Simpson and Shannon

diversities are lowest) than it is in 2020 (when these measures are highest)? What is the correlation between the diversity in a force structure and its robustness? How does this vary with respect to the diversity measures used (Simpson, Shannon, Weitzman, etc.)? These are important questions for the force-structure-analysis community to consider.

Finally, adaptability is a measure of a force structure's capacity to change its composition over time in response to changes in the environment. The ability to adapt is critical for systems operating in environments where fitness is dynamic—a characterization applicable to all complex adaptive systems.[18] That a certain amount of diversity contributes to adaptability in general systems is well understood, but the relationship between diversity and adaptability of force structures remains largely unexamined.[19]

Models

The metrics described above are fundamentally incompatible with the tools available to the force-structure-analysis community in the Air Force. As described in chapter 3, the number of scenarios available to inform any given analysis of force structure is quite small and relatively homogeneous. This shortfall limits the potential for developing effective measures of force-structure flexibility. Further, most force-structure analysis is fundamentally reductionist in the sense that different portfolios (combat air forces; mobility forces; intelligence, surveillance, and reconnaissance forces; etc.) are each analyzed separately, and recommendations for force sizing in each portfolio are then collated.[20] Questions of robustness are fundamentally tied to the relationships among force-structure elements—the interdependence intrinsic to complex adaptive systems. This disaggregation limits the potential for analysis of robustness. Finally, as previously noted, force-structure analysis in the Air Force almost entirely ignores the evolutionary process and performance of force structures in the years intervening between widely separated time frames. The tools with which the Air Force is equipped to conduct its analyses are shaped by this reality, sharply limiting the capability to analyze the evolution and adaptation of force structure.

The measures offered above imply a need for analytical tools with certain characteristics and capabilities. First, the question of flexibility imposes a need for a substantially larger collection of potential scenarios than is currently the norm. This necessity, in turn, implies a capability to rapidly generate scenarios—perhaps via some automated means.[21] Second, the question of robustness demands tools capable of identifying (or facilitating the identification of) vulnerabilities in force structures and developing innovative means

to exploit them.[22] Finally, the study of the evolutionary dynamics of force structures through time is critical to assessing factors such as the adaptability and long-term viability of force structures and potential path-dependent pathologies.[23]

Manpower

Thomas Kuhn's model for the structure of scientific revolutions begins with the definition of a *paradigm*—a set of "accepted examples of actual scientific practice" that "provide models from which spring particular coherent traditions of scientific research."[24] These models comprise the canonical examples, underlying assumptions, and common language defining the questions of interest for a scientific community and the acceptable means for pursuing their answers. The application of these means to the questions framed by a foundational paradigm constitutes what Kuhn calls normal science or mopping-up operations—the filling in of the details implicit in articulating a paradigm. It is this activity that occupies the majority of a scientist's time and career.[25] It is precisely this normal science—based on a prevailing paradigm that views force structure as something other than a complex adaptive system—that comprises the bulk of force-structure analysis in the Air Force.

According to Kuhn, in the course of conducting this normal science, anomalies or discrepancies will emerge between observed results and results predicted under the operating paradigm.[26] At some point, accumulated anomalies constitute a challenge to the accepted paradigm and generate a crisis in the scientific community's acceptance of it. The argument that force structures are complex adaptive systems but that the analytic community of the Air Force does not treat them as such (see chaps. 2 and 3) represents the articulation of accumulated anomaly. In the Kuhnian revolution, when these anomalies and the associated crisis are coupled with the presentation of a more attractive alternative paradigm (also described in chaps. 1 and 2), the old paradigm may be rejected in favor of the new.[27] This fresh paradigm supplants the old entirely and frames a new science. In this case, the new science is the analytic treatment of force structure as a complex adaptive system.

To make changes of the magnitude described in the measures and models used in force-structure analysis, however, requires an adjustment of the canonical examples and underlying assumptions regarding force structure. This paradigm shift or analytic revolution can become self-sustaining, however, only through the inculcation of the new paradigm in each succeeding generation. According to Kuhn,

> Scientists, it should already be clear, never learn concept, laws and theories in the abstract and by themselves. Instead, these intellectual tools are from the start encountered in a historically and pedagogically prior unit that displays them with and through their applications. A new theory is always announced together with applications to some concrete range of natural phenomena; without them it would not even be a candidate for acceptance. After it has been accepted, those same applications or others accompany the theory into the textbooks from which the future practitioner will learn the trade. They are not there merely as embroidery or even as documentation. On the contrary, the process of learning a theory depends upon the study of applications, including practice problem-solving both with a pencil and paper and with the instruments of the laboratory. . . . That process of learning by finger exercise or by doing continues throughout the process of professional initiation. As the student proceeds from his freshman course to and through his doctoral dissertation, the problems assigned to him become more complex and less completely precedented. But they continue to be closely modeled on previous achievements as are the problems that normally occupy him during his subsequent independent scientific career.[28]

In other words, the inculcation of the paradigm in a professional scientific community takes place in the normal course of educating prospective members of that community. Therefore, altering the curriculum to which those prospective members are exposed is necessary to effect change in the prevailing paradigm. Further, this change should encompass both initial indoctrination (i.e., the freshman course) and advanced and continuing education (i.e., the doctoral dissertation).

On accession into the Air Force, newly commissioned lieutenants slated to become operations analysts go to Fort Lee, Virginia, and the Army Logistics University for initial training in the Operations Research/Systems Analysis (ORSA) course. This is the same course to which Army officers are sent on being selected for training as ORSA professionals.[29] The course is divided into two phases. The first phase includes four weeks of instruction and covers "a comprehensive block of instruction in probability and statistics, as well as a review of calculus" while the second covers graduate-level operations-research methods.[30] The Air Force and Army differ in the composition of their respective operations analyst and ORSA career fields in that Air Force officers enter service as operations analysts while Army officers are selected for this duty as captains or majors. It is this difference that necessitates a four-week refresher program for Army officers long separated from their undergraduate education and presents an opportunity for the Air Force. Air Force officers attending this Phase I refresher program are new graduates in mathematics, statistics, operations research, and other related fields, rendering the program largely redundant for them.[31] Rather than eliminating the program for Air Force officers, however, it might be possible to develop an alternative curriculum in place of the four-week Phase I program and introduce them to the theory and practice of complex systems as a *supplement* to the traditional (and important) opera-

tions research methods presented in Phase II. Thus, at effectively zero cost, the force-structure analysis community in the Air Force may begin the incremental alteration of the prevailing analytic paradigm.

The alteration need not involve only the introductory education afforded incoming operations analysts, however. Opportunities for low-cost exposure to continuing education in the field of complex adaptive systems are readily available. For example, the New England Complex Systems Institute in Cambridge, Massachusetts, offers two courses in the theory and modeling of complex physical, biological, and social systems. For full-time graduate and undergraduate students, these intensive programs are available for approximately $850 each, and arranging course credit at the student's home institution is possible.[32] Similarly, the Santa Fe Institute offers a summer school program comprising "an intensive introduction to complex behavior in mathematical, physical, living, and social systems for graduate students." The 2014 offering of this program involves $3,500 in tuition, covering participation, course materials, accommodations, and meals.[33] Both programs offer an opportunity to supplement the graduate education offered to students in the Department of Operational Sciences at the Air Force Institute of Technology at very low cost to the Air Force and without imposing new curriculum requirements on that institution. In this way, a primary source for force-structure analysts in the Air Force can be easily and inexpensively adapted to provide advanced education in both the traditional methods of operations research and the methods of complex adaptive systems.

Further, the opportunities associated with the New England Complex Systems Institute and the Santa Fe Institute are not limited to the educational programs they offer. Each also supports postdoctoral research fellows. For a limited investment, the Air Force could conceivably support research in complex adaptive systems as they are or might be applied to the study and understanding of force structure and force planning.

Conclusion

Empirically it is well known that the behavior of the overall system often is not implicit in the behaviors of its individual elements. In modern scientific parlance, this describes a complex adaptive system. Such systems are distinguished by being comprised of diverse, interdependent, adaptive elements interacting nonlinearly and exhibiting systemic behaviors including emergence, coevolution, and path dependence across multiple scales. Further, material force structures and the strategic environment they help to define are undeniably counted among these complex systems. In other words, "the world

is more a place of instability, discontinuity, synergies, and unpredictability" than force-structure analysts would prefer.[34]

While it is demonstrably true that force structures are complex systems, the force-structure analysis community in the Air Force has consistently denied this nature. This repudiation need not continue, however. Changing the prevailing paradigm of force-structure analysis in the Air Force is possible—without substantial upheaval in that community or the imposition of significant cost. On the other hand, the cost of not treating the complex system of force structure in a manner congruent with its nature may be extraordinarily high if it affects the capacity of the Air Force to fulfill its statutory responsibilities or if it leaves the Air Force and the nation vulnerable to surprise. One of the founders of modern complex systems theory, Per Bak, says of complex adaptive systems, "The basic idea is that large, dynamical systems naturally evolve, or self-organize, into a highly interactive, critical state where a minor perturbation may lead to events, called avalanches, of all sizes. The system exhibits punctuated equilibrium behavior, where periods of stasis are interrupted by intermittent bursts of activity."[35] These bursts of activity are not only sporadic and difficult (or impossible) to predict, they are also out of proportion to expectations generated by simple systems thinking. To view the world as it is not and to act on that view introduces potentially catastrophic—and unacknowledged—risk in those actions. The question of national security is too important to be treated thus, and the solutions are too simple to be denied.

Notes

1. Mann, "Chaos, Criticality, and Strategic Thought," 34.

2. Clausewitz, *On War*, 149.

3. While this discussion centers entirely on the Air Force, the opportunities presented are equally applicable to other services and to the DOD as a whole. Further, while the focus here is implicitly at the level of Headquarters USAF, the ideas presented may scale to other levels of analysis (i.e., major command, numbered air force).

4. Such studies have been conducted in a variety of fields, so the effort with respect to force-structure analysis need not begin from nothing. For example, see Weitzman's articles "What to Preserve?," 157–83, and "Noah's Ark Problem," 1279–98.

5. Quoted in Osinga, *Science, Strategy, and War*, 218.

6. Scott Page combines a collection of mechanisms—specialization, responsiveness, synergy, redundancy, competition, collective knowledge, modularity, and cross-cleavages—under the rubric of robustness. For this discussion, we refer to the effect sought (e.g., flexibility or robustness) rather than the mechanism through which it is achieved. Not all of Page's mechanisms will be treated here, but they may provide additional opportunities for future analysis. See Page, *Diversity and Complexity*, 197–248.

7. This definition is not inconsistent with the concept of flexibility as articulated in Air Force doctrine: "Flexibility allows airpower to exploit mass and maneuver simultaneously.

Flexibility allows airpower to shift from one campaign objective to another, quickly and decisively." AFDD 1, *Air Force Basic Doctrine*, 39–40. Flexibility here is fundamentally equivalent to the mechanism of responsiveness examined in Page, *Diversity and Complexity*, 197–202.

8. Ashby, *Introduction to Cybernetics*, 207.

9. Note that the scenarios/disturbances discussed here cross multiple scales. Two different scenarios might involve disparate theaters of war, adversaries, etc. At another scale, they might involve the same adversary and similar goals with a change in some substantial environmental factor (e.g., basing constraints imposed by allied nations), a divergent set of adversary objectives, or alternate strategies employed to achieve given objectives.

10. Page refers to the mechanism through which this effect is achieved—redundancy—rather than to the effect itself. *Diversity and Complexity*, 227–36.

11. Ehrlich and Ehrlich, *Extinction*, xii–xiii.

12. These two forms of redundancy are often referred to as pure redundancy and degeneracy. See Page, *Diversity and Complexity*, 228. This discussion of redundancy makes it especially clear that the mechanisms through which diversity operates to provide robustness in a complex system are not mutually exclusive. Note the connection between degenerate redundancy and responsiveness, for example. The bucket of sand and the bucket of water are qualitatively different and thus operate on different forms of fire. A bucket of water is not an appropriate means for extinguishing an electrical fire, for example. With respect to a typical campfire, however, the functionality of the two extinguishers is identical. Thus, this example exhibits characteristics of both responsiveness and redundancy.

13. This is known as the redundancy-diversity tradeoff (ibid., 227).

14. Ehrlich and Ehrlich, *Extinction*, xiii.

15. Biologist and ecologist Robert T. Paine coined this term based on his study of the relationship between starfish (predators) and mussels (prey) in the coastal intertidal regions in Washington. See his articles "Food Web Complexity," 65–75, and "Note on Trophic Complexity," 91–93.

16. For a discussion of scale, see Bar-Yam, *Making Things Work*, 54–59,

17. Ferran and Chuchmach, "Some F-22 Pilots Don't Want to Fly."

18. See Page, *Diversity and Complexity*, 151–66.

19. Ibid., 217–24. Some tentative attempts at characterizing this relationship have been made. For example, see Murphy, Payne, and VanDerWoude, "Revolutionary Methods."

20. Maj Gen Jack Weinstein (director of programs, Office of the Deputy Chief of Staff for Strategic Plans and Programs, Headquarters USAF, Washington, DC), interview by the author, 15 February 2012.

21. One approach with potential might include the use of genetic algorithms to evolve scenarios. They have been used in describing force structures with high utility across multiple scenarios. For example, see Bennett, "Robust Multi-Scenario Optimization." From an adversary's perspective, however, each new force structure in the algorithm comprises a new scenario. Further, chapter 2 demonstrated—in the context of the Prisoner's Dilemma—that behavior can be modeled with a genetic algorithm. While that was a simple example of behavioral evolution, a concept of operations is nothing more than a behavioral strategy. Using tools like these, creating such scenarios en masse seems eminently possible. An ancillary benefit of this approach is its application to US forces as well, with the potential to uncover innovative operating concepts and possibilities for joint-force experimentation.

22. The described methods are side neutral. This implies that an ancillary benefit is to highlight potential vulnerabilities in adversaries as well as in US forces. Thus, investment strategies for force structure in both offensive and defensive senses may be suggested.

23. An effort is under way under the leadership of Air Force Studies and Analyses, Assessments, and Lessons Learned (HQ USAF/A9) to develop such tools, but this development effort remains in the formative stages. Dr. Mark Gallagher (technical director, HQ USAF/A9, Washington, DC), interview by the author, 23 February 2012.

24. Kuhn, *Structure of Scientific Revolutions*, 10.

25. Ibid., 24.

26. Ibid., 65.

27. Ibid., 77.

28. Ibid., 46–47.

29. Henningsen, interview; and Army Logistics University, "History of the Army Logistics University."

30. Army Logistics University, "Courses," Operations Research/Systems Analysis, Phases I and II.

31. Henningsen, interview.

32. New England Complex Systems Institute, "NECSI Summer and Winter School." The rates given here are for 2014 offerings.

33. Santa Fe Institute, "2014 Complex Systems Summer School."

34. Yarger, *Strategy and the National Security Professional*, 33. Yarger, in this context, is referring to operational planners rather than to force-structure analysts, but the issues described are precisely parallel.

35. Bak and Paczuski, "Complexity, Contingency, and Criticality," 6690.

Abbreviations

AFDD	Air Force doctrine document
AWACS	Airborne Warning and Control System
CFAM	Combat Forces Assessment Model
C2	command and control
DOD	Department of Defense
FYDP	Future Years Defense Program
ISR	intelligence, surveillance, and reconnaissance
JSTARS	Joint Surveillance Target Attack Radar System
LAAR	light attack and reconnaissance
LiMA	light mobility aircraft
LO	low observable
MCDP	Marine Corps doctrine publication
NASA	National Aeronautics and Space Administration
OR	operations research
ORSA	Operations Research/Systems Analysis (course)
PRC	People's Republic of China
QDR	*Quadrennial Defense Review*
RMA	revolution in military affairs
RPA	remotely piloted aircraft
SFI	Santa Fe Institute
UAS	unmanned aerial system
UAV	unmanned aerial vehicle

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